An Investigation into Factors Affecting the Efficacy of Oil Removal from Wildlife Using Magnetic Particle Technology

A thesis submitted for the degree of Doctor of Philosophy

by

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Declaration

I, Hien Van Dao, declare that the thesis entitled "An Investigation into Factors Affecting the Efficacy of Oil Removal from Wildlife using Magnetic Particle Technology" is no more than 100,000 words in length, exclusive of tables, figures, appendices, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

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Publications

1. Orbell, JD, **Dao, HV,** Ngeh, LN, Bigger, SW, Healy, M, Jessop, R, Dann, P 2005, ‘Acute temperature dependency in the cleansing of tarry feathers utilizing magnetic particles’, *Environ. Chem. Letters*, vol. 3, no. 1, pp. 25-27.

2. Orbell, JD, **Dao, HV,** Ngeh, LN, Bigger, SW 2005, ‘Magnetic particle technology in environmental remediation and wildlife rehabilitation’, *Proceedings of the 9th Annual Environmental Postgraduate Conference*, Hobart, Australia, 29 Nov- 2 December, 2005, pp. 1-7.

3. **Dao, HV,** Maher, LA, Ngeh, LN, Bigger, SW, Orbell, JD, Healy, M, Jessop, R, Dann, P 2006, ‘Removal of petroleum tar from bird feathers utilising magnetic particles’, *Environ. Chem. Letters,* vol. 4, no. 2, pp. 111-113.

4. **Dao, HV,** Ngeh, LN, Bigger, SW, Orbell, JD 2006, ‘Achievement of 100% removal of oil from feathers employing magnetic particle technology’, *J. Environ. Eng.*, vol. 132, no. 5, pp. 555-559.

5. Orbell, JD, **Dao, HV,** Ngeh, LN, Bigger, SW 2006, ‘Magnetic particle technology in environmental remediation and wildlife rehabilitation’, the *Environmentalist* (In Press).

6. **Dao, HV**, Ngeh, LN, Bigger, SW, Orbell, JD, Healy, M, Jessop, R, Dann, P 2006, ‘Magnetic cleansing of weathered/tarry oiled feathers - the role of pre-conditioners’, *Mar. Pollut. Bull.*, vol. 52, no. 12, pp. 1591-1594.

7. **Dao, HV,** Ngeh, LN, Bigger, SW, Orbell, JD 2004, ‘The use of magnetic particle technology in the cleansing of oiled birds’, Abstract, *Proceedings (on a CD Rom) of the workshop on Improving Oiled Wildlife Preparedness and Response in Australia*, Australian Maritime Safety Authority (AMSA), Australia.

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9. **Dao, HV,** Ngeh, LN, Bigger, SW, Orbell, JD 2005, 'Critical temperature dependency in the cleansing of tarry/weathered oiled feathers using magnetic particle technology', Abstract, *New Zealand Journal of Zoology*, vol. 32, pp. 266-267.

Conference and Workshop Presentations

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2. **Dao, HV,** Ngeh, LN, Bigger, SW, Orbell, JD, '*The application of magnetic particle technology in cleansing of oiled wildlife'*, 12th Annual Conference of the RACI Analytical and Environmental Chemistry Division R&D Topics, the University of Melbourne, Melbourne, Australia, 5-8th December 2004.

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Abstract

Utilising iron powder as a dry cleansing agent, factors affecting the efficacy of the magnetic removal of oil contamination from a variety of matrices, including feathers and plumage, have been investigated. Employing electron microscopy and an established gravimetric methodology, detailed investigations into the effect of particle size, particle structure and surface texture have been carried out, demonstrating that the efficacy of removal can be successfully manipulated by varying such properties. Consequently, a grade of particle has been identified whereby, within experimental error, 100% removal of a variety of contaminants from a number of different matrices, including feathers, can be achieved. Having identified these improved particles, their ability to remove tarry and weathered/tarry residues from feathers and plumage has been explored. The effect of the ambient temperature at which cleansing takes place has been shown to be important in regard to the latter. Temperature dependent *in vitro* studies on duck and penguin feather clusters and penguin carcasses, contaminated by "worst case scenario", highly viscous, tarry oil, have been carried out using established gravimetric methodologies. A remarkable temperature dependency for contaminant removal has been observed for both feather clusters and plumage whereby, below and at certain temperatures, little removal is achieved but, above these temperatures, the removal rapidly approaches 100%. It is notable that this phenomenon occurs within a narrow temperature range of only a few degrees and the high level of removal is achieved at a temperature that is well below the temperature at which the tarry residue becomes a flowing liquid. These results hold promise that a very high removal of tarry residue from feathers is possible, under temperature conditions that would be benign to a bird. In order to explain the phenomenon, the thermodynamics of the process have been investigated. These studies show the process to be highly endothermic and entropy driven, hence providing insight into the phenomenon. Similar experiments, above the acute temperature, carried out on tarry residue that had been allowed to weather for different periods of time, demonstrated that the same high levels of removal can be achieved, although the initial removals were lower for longer periods of weathering.

The role of pre-conditioners used in conjunction with magnetic cleansing has also been investigated. It is found that pre-conditioners enhance the optimum removal and

reduce the number of treatments required to achieve this. It has been demonstrated that the application of a pre-conditioner approximately half way through the treatment achieves the maximum advantage. The magnetic cleansing technique lends itself to, and has been successfully applied to, the relative quantitative assessment of a range of candidate pre-conditioners. These indicators are also expected to carry over with fidelity to the use of pre-conditioners for more conventional detergent-based cleansing.

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THIS THESIS IS DEDICATED TO MY LOVING PARENTS

List of abbreviations

AMSA	Australian Maritime Safety Authority
AO	Arab medium crude oil, Exxon Mobil
A40S	Atomised coarse un-annealed grade of iron powder
A100S	Atomised fine un-annealed grade of iron powder
ASC100.29	Atomised fine annealed grade of iron powder
ASC300	Atomised superfine annealed grade of iron powder
B (%)	Ratio of the weight of the feather cluster before and after treatment in the blank test experiments
BOD	Biological oxygen demand
BO1	Bunker oil 1, International bunker supplies (IBS)
BO2	Bunker oil 2, International bunker supplies (IBS)
COD	Chemical oxygen demand
CSIRO	Commonwealth Scientific and Industrial Research Organisation
C (%)	Percentage of contaminant removal from plumage
CV	Co-efficient of variance
C100.29	Spongy fine un-annealed grade of iron powder
DDG	Distiller's dried grain
DPIWE	Department of Primary Industries, Water and Environment
DOC	Dissolved organic carbon
E	Pre-conditioner efficiency parameter
EO	Engine oil, Mobil
ES1	50% (v/v) Gippsland crude oil/seawater emulsion
ES2	50% (v/v) Engine oil/seawater emulsion
F (%)	Percentage of contaminant removal from feather clusters
F_o (%)	Maximum value of F (%)
GO	Gippsland crude oil, Exxon Mobil
IBRRC	International Bird Rescue Research Centre
IPIECA	International Petroleum Industry Environmental Conservation Association
ITOPF	International Tanker Owners Pollution Federation Limited
k	Efficiency constant in the empirical model
K_{mole}	Mole-based equilibrium constant

K_{mass}	Mass-based equilibrium constant
MO	Merinie crude oil, Exxon Mobil
MPT	Magnetic particle technology
MSDS	Material Safety Data Sheet
M40	Spongy coarse un-annealed grade of iron powder
MH300.29	Spongy superfine annealed grade of iron powder
NOAA	National Oceanic Atmospheric Administration
NRC	National Research Council
N	Number of treatments
N_{99}	Effective number of treatments to achieve 99% of contaminant removal
NC100.24	Spongy fine annealed grade of iron powder
OWCN	Oiled Wildlife Care Network
P (%)	Percentage of contaminant removal from a glass substrate
P_o (%)	Maximum value of P (%)
R	Particle-to-contaminant ratio
R_o	Maximum value of R needed to achieve P_o (%)
S	Standard deviation
SANCCOB	Southern African Foundation for the Conservation of Coastal Birds (*sic*)
SEM	Scanning Electron Microscope
SE	Standard errors
SO	Shell crude oil, Shell
T	Temperature
TSBRR	Tri-State Bird Rescue and Research
RSNA	Russian Science News Agency
UCT	University of Cape Town
USEPA	US Environmental Protection Agency
USFWS	US Fish and Wildlife Service
95%	95% interval confidence
$\Delta G°$	Gibbs free energy
$\Delta H°$	Enthalpy
$\Delta S°$	Entropy

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CHAPTER 1: INTRODUCTION

1.1 The impact of oil spills on the environment

With economic development, humans exploit and consume petroleum more and more in order to meet their increasing demands. This leads to oil pollution that has been impacting upon the marine environment, with many ecological and economic consequences, for the best part of a century (Etkin, 1999; ITOPF-a, 2004). Annually, it is estimated that 1,300,000 tonnes of oil goes to the sea (NRC, 2003), around 53% of which comes from human activities such as petroleum extraction, transportation and consumption, and the remaining 47% is caused by natural seepage (IPIECA, 2005).

Oil spills have a wide variety of impacts on the environment, in particular on marine ecosystems (ITOPF-b; 2004). The degree of impact depends on many factors including: volume and type of oil spilt, weather conditions and seasons, physical characteristics of the affected area (AMSA, 1999; ITOPF-a, 2004). Impacts can be either short or long term (AMSA, 1999). Long-term effects usually require from 2 - 10 years for recovery (Kingston, 2002). Immediate effects are widespread and impact significantly on marine ecosystems. A variety of marine life is affected, including benthic invertebrate, plankton, fish, mammals and birds (Edgar *et al.*, 2003; Heubeck *et al.*, 2003). Moreover, oil spills also cause negative impacts on coral reefs, mangroves, salt mashes, rocky and sedimentary shores (Smith, 1983). The economic effects of oil spills can be severe with fishery, mariculture, tourism and many other coastal activities being affected (ITOPF-a, 2004).

1.2 The impact of oil spills on birds

Birds are particularly vulnerable to oil pollution since they are very mobile and easily encounter oil contamination (Smith, 1983). An oil spill has the potential to affect large numbers of birds (Camphuysen & Heubeck, 2001; IBRRC-b, 2004), and there is an imperative to attempt efficient rescue and rehabilitation. For example, in the North Atlantic alone, it is estimated that at least one million birds are killed by oil pollution annually (Welte and Frink, 1991). The *Exxon Valdez* oil spill, which occurred in 1989, is believed to have killed more than 30,000 birds (Piatt *et al.*, 1990). When a bird encounters oil and survives the initial trauma, it can also suffer ongoing effects (IPIECA, 2004) described as follows:

External effects include (OWCN, 1999; IPIECA, 2004) feather disruption leading to hypothermia, reduced buoyancy, impaired flying ability and reduced ability to hunt for food and to escape from predators (Cooper and Eley, 1979; Welte and Frink, 1991; Walraven, 1992). Blindness can also occur if oil contacts with birds' eyes (Liu and Lipták, 1997).

Internal effects may include pneumonia from oil inhalation (Jenssen, 1994), anaemia following absorption of toxic chemicals via the skin (Welte and Frink, 1991; Walraven, 1992; Jenssen, 1994), acute toxicity to the gastro-intestinal tract and other organ systems (Walraven, 1992), impairment of the immune system (Briggs *et al.*, 1997) and disruption of thermal balance (Jenssen and Ekker, 1989; Jenssen, 1994). Poisoning of birds can also occur due to oil ingestion by preening (Cooper and Eley, 1979; Welte and Frink, 1991; Walraven, 1992; Jenssen, 1994).

Figure 1.1: Oiled penguins (UCT-a, 2005).

Secondary and long-term effects include the reduction of reproductive success, decreased growth rate and body weight, decreased fertility of eggs, increased mortality of embryos (Welte and Frink, 1991; Jenssen, 1994), behaviour and weight changes and the accidental oiling of eggs and offspring (Burger and Tsipoura, 1997). Secondary effects can also arise as a result of prolonged periods of time in captivity (OWCN, 1999). This includes vulnerability to infectious disease and stress and pressure sores in the birds' joints and feet. Long-term effects have also been reported in research by Anderson *et al.* (2000) which indicates that oiled birds that have been rehabilitated successfully remain in a state of lower health and continue to suffer impairments in survivability as well as behavioural changes.

As a result of an oil spill, the habitat itself may be altered, affecting food sources and other species with which the contaminated animal interacts (Smith, 1983).

1.3 Traditional techniques for oil spill remediation

The serious environmental consequences of oil spills have long been recognized and considerable research and technological development has been carried out to develop appropriate remediation techniques (Suni *et al.*, 2004; Ventikos *et al.*, 2004). These techniques generally fall into four categories (Mullin and Champ, 2003; Ventinkos *et al.*, 2004), namely: mechanical/physical recovery (booms, skimmers, sorbents), chemical treatment (dispersants, emulsion breakers; gelling agents, sinking agents), bioremediation and in-situ burning. Fig. 1.2 details such oil spill remediation techniques. A more detailed description of these methods together with literature references is provided in Appendix 1.

1.4 Rehabilitation of oiled birds

In the rehabilitation of oiled birds the objectives are the rescue, treatment, cleaning and, ultimately, the release of the healthy animals to the natural environment (Anderson *et al.*, 2000; USFWS, 2002).

According to Welte and Frink (1991), Frink and Crozer-Jones (1986; 1990) and IBRRC-a (2004) there are several basic steps involved in the rehabilitation of a contaminated bird. These are: ***(i)*** stabilisation of the oiled bird ***(ii)*** cleaning of oil from the bird ***(iii)*** removal of the cleaning agent from the bird's feathers ***(iv)*** restoration of its water proofing ability, and finally ***(v)*** acclimation of the bird for release. These are described in more detail as follows:

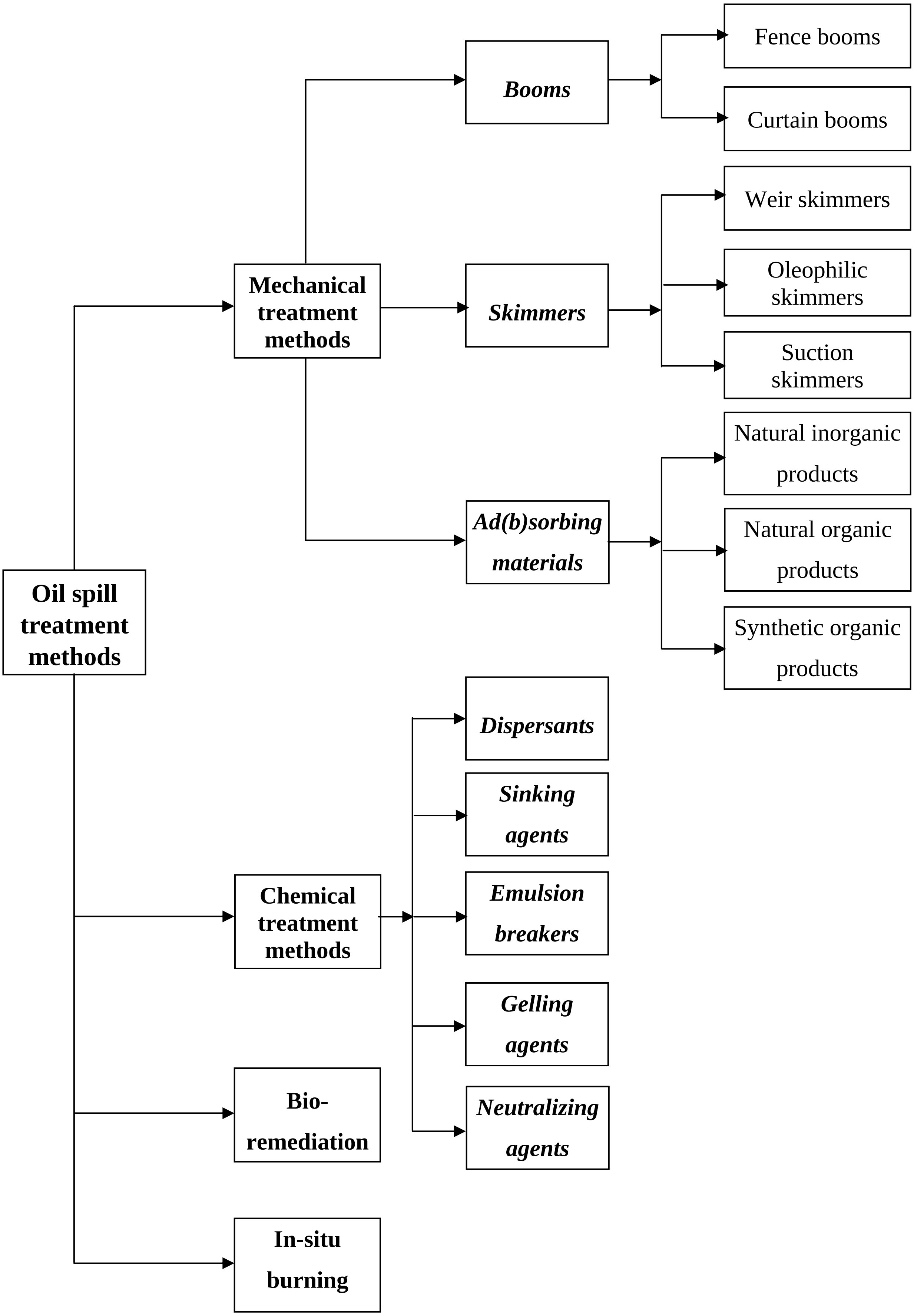

Figure 1.2: Oil spill treatment methods.

(i) Stabilisation of the oiled bird. The objective of stabilising an oiled bird is to reduce the toxic effects of ingested oil and to prepare the bird for cleaning (Welte and Frink, 1991). Stabilisation of an oiled bird is very important (IBRRC-a, 2004) and includes several procedures that are ideally carried out within 2-4 hrs of capture (USFWS, 2002). Firstly, general information about the bird, such as date and location of capture, sex and species of the bird, clinical status of the bird and degree of oiling is recorded. Secondly, the bird is given a physical examination and its weight and temperature is recorded. If the victim is found to be hypothermic or hyperthermic, further examination needs to be postponed and measures taken to solve the problem such as using warm water bottles to reduce hypothermia (OWCN, 1999). Part of the stabilization treatment also involves the removal of excess oil from nares, mouth and vent - usually employing cotton swabs (Welte and Frink, 1991; OWCN, 1999). The bird's eyes are then flushed with a special solution such as sterile saline 0.9% (Frink and Crozer-Jones, 1986; 1990; Welte and Frink, 1991).

Subsequent steps involve the administration of a suspension of activated charcoal that will absorb ingested oil (Holcomb and Russell, 1999). If the bird is dehydrated then re-hydration solutions such as Pedialyte, Lactated Ringers and 2.5% Dextrose, Normosol (Frink and Crozer-Jones, 1986; Welte and Frink, 1991) are administered. Oral administration of fluids to birds is very important and has been demonstrated to lead to an increase in their survival rate (Hill, 1999). In some cases fluids must be given intravenous or intraosseous routes to achieve adequate hydration. Subsequently, the bird is housed in a well-ventilated, newspaper-lined cardboard container in a quiet place before pursuing the next steps (IPIECA, 2004). When the bird is considered calm and stable, it is given a slurry of commercial high protein piciverous bird chow with vitamins and minerals and subsequently fed fish (Clark *et al.*, 1997) in order to recuperate and prepare it for the next step, i.e. the washing procedure.

(ii) Cleaning of oil from the bird: After the bird is stabilised, it is subjected to the removal of oil from its feathers, using cleaning agents and water. Since cleaning is very stressful, the bird needs to be strong enough to meet certain criteria (OWCN, 1999). The most common method for cleaning oil from birds is the use of warm water and detergents. There are normally two persons involving in the cleaning process. In the case of large birds, three persons might be required (Frink and Crozer-Jones, 1986). Hence this process is quite labour intensive. It is necessary during the cleaning process that a sufficient amount of warm water (at ca. 40 ^{o}C), normally 304 to 380 litres (80 to 100 gallons), is provided for a 20-minute wash (Frink and Crozer-Jones, 1990). If detergent is used as a cleaning agent, the concentration usually ranges from 2-15%, depending on the properties of the oil to be removed (Welte and Frink, 1991). These days, washing liquids such as Dawn™, Fairy™ and Dreft™ are often preferred, the concentration recommended being 1-2% (v/v) (OWCN, 1999). Detergents/washing liquids and warm water are prepared in a suitable tub beforehand. The bird is ladled with detergent solutions and its feathers are gently stroked in the direction of feather growth. Care should be taken with respect to the bird's eyes by flushing them with sterile water. When the water becomes oily, the bird needs to be moved to a new tub. The washing process is repeated until no sign of oil is seen on the feathers or in the water. Usually, 10 – 15 tubs are a matter of normality (IBRRC-a, 2004). If oil is tarry, special procedures are needed (Walraven, 1992; Gilardi and Mazet, 1999; Hill, 1999; OWCN, 1999; USFWS, 2002).

(iii) Removal of the cleaning agent from the bird's feathers: Once the bird is cleaned of oil, the next step is to rinse the bird in order to remove the cleaning agent from its feathers (USFWS, 2002). Any detergent or solution residue left on the bird's feathers can impair waterproofing abilities. The bird is then rinsed with warm water (ca. 40 ºC). The rinsing process is continued until there is no visible evidence of detergent on the bird.

(iv) Restoration of its water proofing ability: The next step is to dry and restore the feathers. This is very important since if the feather structure is disrupted or cannot be restored, the bird is not ready to be released. After washing and rinsing, the bird is then padded with clean towels. It is then placed in a drying room with the temperature between 35 to 40 ºC. Suitable equipment for drying birds can include heat lamps or pet dryers (USFWS, 2002). The bird is kept in a clean area and given access to food and water (Frink and Crozer-Jones, 1986; Welte and Frink, 1991). The medical situation of the bird is also monitored and treatment provided as required. After 24 hours, the bird is usually permitted to access water pools where it can gradually restore its feather structure by swimming, diving and preening. Softened fresh water is strongly recommended as it keeps salt crystals from forming and disrupting barbule alignment and results in much faster water proofing. Usually, the time for cleaning the bird and restoring its plumage varies from 48 - 96 hrs (Welte and Frink, 1991).

(v) Acclimation of the bird for release: The final step is acclimation and evaluation of the bird prior to release. This is achieved by exposing the bird to outside weather conditions for a 24 – 48 hr period prior to release. The bird is also provided with a solution of 2.0% saline to stimulate and evaluate the salt gland function (Frink and Crozer-Jones, 1986; Welte and Frink, 1991). A ready-to-release bird must meet all standard medical requirements such as being active, waterproof and healthy (OWCN, 1999). The bird should be banded before release to allow post-release monitoring.

Of all the steps mentioned above, the cleaning and washing stage is critical (Norman, 2003; Bryndza, 2005). Thus, a considerable amount of research has been focused on cleaning methods for oiled birds (Newman *et al.*, 2003; OWCN-b, 2003). This will be discussed in more detail in the following sections.

1.5 Various protocols for cleaning oiled birds

As indicated above, birds are amongst the most vulnerable species with respect to oil spills (IBRRC-b, 2004). Consequently, a considerable amount of research on the protocols for cleaning oiled feathers and for the rehabilitation and treatment of oiled birds has been carried out (OWCN-b, 2003; Parsons & Underhill, 2005).

Figure 1.3: Cleaning oil from bird with water and detergents (UCT-b, 2005).

The outcome of the specific treatment protocol depends on factors such as the techniques employed as well as the type of cleaning agent (and/or pre-conditioner) used. In the cleaning of oiled birds, the type and the effectiveness of cleaning agent is an important consideration (Berkner *et al.*, 1977). Many cleaning agents and techniques have been trailed over time dating back to the 1940s (Berkner, 2005), and, in general, they can be grouped as follows:

1.5.1 Cleaning oiled birds with solvent

In the 1970s, a method for the removal of oil from feathers involved the use of solvents such as Shell Sol-70^{TM} (Naviaux and Pittman, 1973; Harris and Smith, 1977). This particular solvent, on a w/w basis, consisted of paraffins (98.9%), aromatics (0.4%), and olefins (0.7%) and was documented to be effective and safe, and could be completely removed from the feathers by evaporation. An organic solvent named Arklone P^{TM}, developed by ICI Limited, was also tested (Clark and Gregory, 1971). This particular solvent has a low boiling and an anaesthetic property and was reported to succeed in cleaning oiled birds, resulting in the plumage remaining watertight (Clark and Gregory, 1971). Another solvent Chevron Isoparaffin^{TM} 150, a highly purified light hydrocarbon solvent, with no aromatic constituents was also employed in cleaning oiled birds (Naviaux, 1972). The use of acetone to remove oil from feathers was also documented (Berkner, 2005).

The use of solvents has resulted in the rehabilitation of oiled birds. However, solvent cleaning agents are, in general, toxic and irritating to the birds (Berkner *et al.*, 1977; Perry *et al.*, 1978; Smail, 1978; Schmidt, 1997; Russell *et al.*, 2003) and to the personnel conducting the cleaning work (Perry *et al.*, 1978). It was reported by Perry *et al.* (1978) that more than 90% of oiled birds cleansed with solvents died within 12 h, due to inhalation of the solvent's vapours and contact of the solvents with the skin. Moreover, the time required for the release of oiled birds treated with solvents is quite long - up to months. Solvents were also reported to strip the natural oil from birds (Naviaux and Pittman, 1973). Subsequent investigations into improved cleaning methods led to the development of detergent-based cleaning agents.

1.5.2 Cleaning oiled birds with detergent

In the 1970s, the possibility of using detergents in the removal of oil from feathers was first investigated by British scientists (Croxall, 1972; Harris and Smith, 1977; Smail, 1978). A variety of powder detergents (Ariel™, Bio-Daz™, Kudos™ soap flakes, Omo™, Surf™) and washing-up liquids (Village™, Co-op Green™, Fairy Liquid™, Winfield™, Keynote™, Lux™, Palmolive™, Quix™, Squeezy™) were tested (Croxall, 1972; Cooper and Eley, 1979; McCulloch and Reilly, 1984). In the United States, researchers at the International Bird Rescue Research Centre (IBRRC) also trialled seven different detergents, namely Amber Lux™, Basic1™, Conco K™, Grease Relief™, Liquid Concentrate™, Nokomis™, Polycomplex A-11™ in the cleaning of 8 types of oil from birds (Berkner *et al.*, 1977). It was found that Amber Lux™, a biodegradable industrial detergent, was the most effective (Berkner *et al.*, 1977; Newman *et al.*, 2003). The introduction of detergents has led to an improvement in the release and survival rate of oiled birds (Randall *et al.*, 1980; Newman *et al*., 2003) and, under ideal circumstances, birds can be released in a matter of days instead of months.

In the 1980s, a continuation of this research resulted in the development of more effective surfactant formulations for cleaning oiled birds, in order to reduce cleaning time and to improve the degree of restoration of feather microstructure. For example, a more efficient surfactant, Taski-Profi™, was developed, cutting cleaning time in half and improving the thermal insulation properties of the feathers (Jenssen and Ekker, 1989). Also in the 1980s, a concentrate dispersant called OSE750™ (Chemserve, Johannesburg, South Africa) was employed in the cleaning of oiled birds by applying it directly onto the oiled patches, and then rinsing it off with hot water (Kerley and Erasmus, 1987).

In the 1990s, more such cleaning agents were developed. One of these was the formulation developed by Bassères *et al.* (1994), which showed an oil removal of 90% from standard duck feathers compared to 30% for the control. A normal metabolic rate was found to be recovered one day after cleaning and thermal insulation was restored four days after cleaning. In 1991 a method for evaluating the efficiency of various types of surfactants for the removal of petroleum contaminants from feathers was developed (Bryndza *et al.*, 1991). A synthetic oil, consisting of thirteen polycyclic aromatic hydrocarbons, representing components present in light crude oils and diesel fuel, was formulated and used as a standard contaminant to assess the removal by different surfactants. It was reported that shampoos and various dishwashing liquids were more suitable than powder detergents with Dawn^{TM} dishwashing liquid being the most effective. Other studies have also suggested Dawn^{TM} as the most suitable and effective cleaning agent (Welte and Frink, 1991; OWCN, 1999; Newman *et al.*, 2003; Gregory, 2006).

Although Dawn^{TM} is now the most popular cleaning agent, recommended for use in wildlife rehabilitation centres worldwide (USFWS, 2002; OWCN-b, 2003; IPIECA, 2004), it does not necessarily work better than other cleaning agents with respect to the removal of some types of contaminants. For example, Biosolve^{TM} or L.O.C^{TM} (Amway) are shown to be more effective than Dawn^{TM} in the removal of bunker oil from feathers (Monfils *et al.*, 2000).

Cleaning methods using detergent-based solutions have improved over time and their application has contributed to the survival of thousands of victims (Newman *et al.*, 2003). In some cases, the release rate and survival rate is quite high, up to 95% and 59%, respectively (Giese *et al.*, 2000; Goldsworthy *et al.*, 2000; DPIWE, 2004), with a release rate of 50-60% being common these days (Schmidt, 1997). Other success stories about oiled wildlife rehabilitation using detergent-based technique are also documented (Jessup, 1998; Nel and Whittington, 2003).

However, this technique is labour intensive (Popino, 1993) and requires a lot of warm water (40 - 45 ^{o}C) for bathing and rinsing. Moreover, detergents can be toxic and irritating (Berkner *et al.*, 1977) as well as resulting in the removal of preening oil (Jenssen, 1994). It is also time consuming (Popino, 1993) since the entire washing process may take up to 60 min (Welte and Frink, 1991), causing a considerable amount of stress to the bird (Briggs *et al.*, 1997). Damage to the essential microstructure of the feathers can also occur (Ngeh, 2002). Apart from the above, it is not possible to employ this technique in the field since the required facilities are not transportable. Consequently oiled wildlife has to be stabilized initially and transported to a centre for subsequent washing.

It is also important to emphasize that, although a number of different detergent cleaning agents have been tested to date, their removal efficiency is, in general, not well-quantified, an exception being the cleaning product developed by Bassères *et al.* (1994). The development of an effective cleaning technique that can routinely quantify the efficacy of oil removal and feather damage is important. Current techniques to rehabilitate oiled wildlife are very costly (Sharp, 1996; Estes, 1998). For instance, after the Exxon Valdez oil spill, approximately $41 million was spent on the rescue, treatment and release of 800 birds (Sharp, 1996) and roughly $17 million on sea otters (Estes, 1998).

Therefore, there are ongoing concerns about oiled bird rescue and rehabilitation using detergent techniques (Jenssen, 1994; Anderson *et al.*, 1996; Sharp, 1996; Schmidt, 1997; Briggs *et al.*, 1997; Estes, 1998; Heubeck *et al.*, 2003; Ronconi *et al.*, 2004), and the search for more effective cleaning techniques and agents continues.

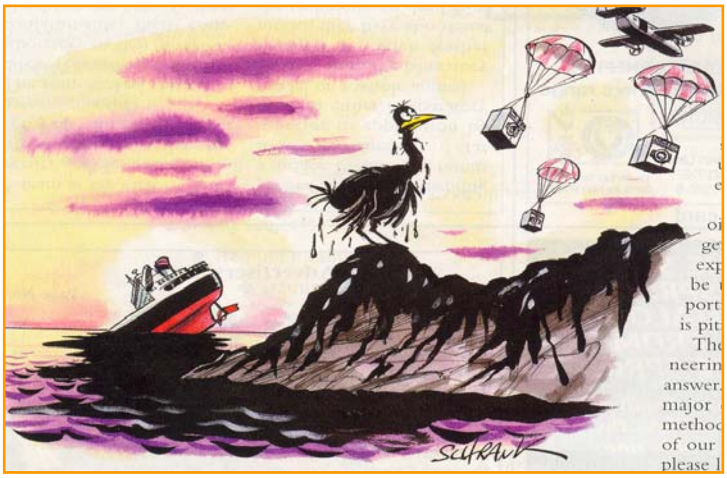

Figure 1.4: A cartoon that indicates the problem of cleaning oiled birds in the field using detergent techniques (Eureka, 1999).

1.5.3 Cleaning oiled birds with other materials

Apart from solvent and detergent, a number of other materials have also been tested with respect to oil removal from wildlife. For examples, as early as 1952 Stedman used a mixture of corn oil, neatsfoot oil, detergent, waxes, solvent and water to clean oiled birds (Newman *et al.*, 2003). Later on, in the 1950s and 1960s, powdered chalk, mascara remover, butter, lard, castor oil, mineral oil and waterless hand cleaner were also tested

(Berkner, 2005). In the 1970s, the use of clays to clean oil from wildlife was also conducted (Holmes, 1973).

More recently, other products were developed and tested to clean oiled wildlife. One of these was Elastol™ - a powdered product that binds oil to water and was applied dry to the oiled feathers before being rinsed off (Eie, 1995). It was suggested that this product could be more effective than detergents/washing liquids and does not remove preening oil. Another agent described as demonstrating "visco-elasticity" was developed for the removal of oil from birds, fish and mammals (Popino, 1993). This cleaning agent was a non-toxic polymer composite having food-grade additive quality and consisting of ca. 80% by weight of polyisobutylene, contained in a low volatile organic solvent. This cleaning agent was sprayed onto the oil patch and the oil-laden cleaning agent was then rinsed off with an "aqueous solution". This product was reported not to remove the natural oils of the animals tested. Another product called Distiller's dried grain (DDG) utilizing corn, wheat or rice, has also been reported in the cleaning of oiled pheasants (Working *et al.*, 1999). This cleaning agent was applied twice on the oiled area of the plumage. The first application was to agglomerate and to remove loose oil, followed by the second application, in the presence of tap water, to sorb the remaining oil. The mixture was then washed off with warm water.

For one reason or another, the above cleaning agents and methods have yet to find a use in wildlife rehabilitation centres worldwide. The investigation into more effective ways of cleaning oiled wildlife is a continuing area of research.

1.5.4 The use of induced moult as a means of cleaning oiled birds

Kerley *et al.* (1985) explored the possibility of artificially inducing moult as a means of cleaning oiled birds. However, this method was found to do more harm than good, and considered to be impractical since the post-moult feathers of the oiled bird are still contaminated and this method is too stressful for an already stressed victim that needs to be recuperated and rehabilitated quickly.

1.5.5 Bird washing machine

A bird-washing machine, named the Elf bird washing machine, has been even manufactured by CHENE Oiled Bird Rehabilitation Centre in France (Hill, 1999; OWCN-b, 2003; IPIECA, 2004). This machine was reported to save a lot of time for cleaning oiled birds, needing only 7 min to clean one oiled bird, compared to two hours by hand (Hill, 1999). Therefore, it has been used in some oil spill cases such as the Pallas spill in Germany in 1999 and the Erika spill in France in 2000. However, due to concern about its efficacy and safety, this kind of machine has yet to be recommended for use in rehabilitation centres worldwide (OWCN-b, 2003).

1.6 The application of magnetic particle technology in environmental remediation and wildlife rehabilitation

1.6.1 Magnetic particle technology and its general application in environmental remediation

There are many diverse applications of magnetic particle technology (MPT) in science and engineering, including mineral treatment, beneficiation of coal, removal of impurities from boiler water in conventional and nuclear power plants and in wastewater treatment (Safarikova and Safarik, 2001). In recent years, environmental pollution has become an urgent issue and many technologies have been developed to address this problem. Magnetic particle technology is a serious contender in this regard.

One of the earliest applications of magnetic particle technology in the environmental area was that conducted at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia (CSIRO, 1989/1990; 1991). These researchers successfully developed a MPT (magnetite particles), the SIROFLOC process, for water clarification and decolourisation (Kolarik, 1983; Anderson *et al.*, 1983). This process has since been employed in water treatment plants in Western Australia, Tasmania and in countries other than Australia including the United Kingdom and Taiwan (Bolto, 1996). This technology has also been extended to sewage treatment with good outcomes. Thus, employed in a pilot sewage treatment plant at Malabat in Sydney, this process can remove 87% of suspended solid, 90% of oil and grease and 60% of COD (chemical oxygen demand). While BOD (biological oxygen demand) is reduced by nearly 50%, the removal percentage for bacteria, phosphate and heavy metals is 99%, 89% and 74-89% respectively (Bolto, 1996). More impressively, this is achieved within 15 min. Also in the 1980s, the use of magnetite particles to adsorb Co(II) ions was also reported (Tamura *et al.*, 1983).

Various types of magnetic materials have been applied to the sorption of dyes (Safarik *et al.*, 1995; 1997; 2002). These include magnetic composites, magnetic charcoal and magnetically labelled bakers yeast cells. In particular, magnetic charcoal has been utilised to treat water-soluble organic dyes belonging to triphenylmethane, heteropolycyclic and azodye groups. For example, one gram of dried magnetic charcoal can maximally adsorb up to 132.5-265 mg of dye. The magnetised yeast cells are made by mixing a 33% (v/v) yeast suspension with “ferrofluid” in a ratio of 3:1 (v/v). They are then heated in a boiling water bath for 15 min before being washed with saline and stored at temperature of 4 ^{o}C. The maximum adsorption capacities range from 19.6 to 430.2 of mg of dye (for five different types of dye) per 1g of magnetically modified yeast cells.

The removal from soil of low-solubility, non-ionic, organic pollutants using a magnetic separation technique has been documented (Park and Jaffe, 1995). In this research, surfactant treated oxides, including magnetite, are utilised to remove phenanthrene from a soil slurry. High gradient magnetic separation techniques have also been used to remove phosphate and heavy metals from wastewater (Val Velsen *et al.*, 1991) as well as heavy metals, such as Cr, from contaminated soil (Rikers *et al.*, 1998).

A company in the USA, Selentec, has developed a technology named MAG*SEP^{SM} to remove a variety of contaminants such as heavy metals and radionuclides from the environment (Dunn and Friedman, 1997). This process uses “MAG*SEP^{SM} particles”, consisting of a magnetic core, a polymer matrix and a selective absorber coating. The MAG*SEP^{SM} particles loaded with contaminant are separated by magnetic devices and can be reused. This technology has now been extended to a full-scale operation in order to decontaminate radionuclides in a radionuclide-affected milk factory in the Ukraine. The removal of radioactive materials, actinides and heavy metals from water using magnetic resin (consisting of polyamine-epichlorohydrin resin beads with ferrites attached to the surface of the beads) has also been reported in US Patent 5,595,666 (Kochen and Navratil, 1997). The possibility of using magnetite in the removal of phosphate from municipal sewage was also investigated (Franzreb *et al.*, 1998). Using this process, the phosphate concentration is reduced from 14 mg/L to 1 mg/L (PO_4^{3-} as P) at filtration rates of about 40 m/h.

Macasek and Bartos (2000) have investigated the use of a magnetic sorbent, a mixture of magnetic iron and nickel oxides, in the removal of radio-cesium and radio-strontium from clay and soil suspensions. In the research of Navratil *et al.* (2000), a number of magnetic sorbents, including iron oxides, magnetite and iron ferrite were also researched in regard to the removal of radionuclides and heavy metals from waste. White and Athanasious (2000) have also reported the use of synthetic magnetic flocs (magnetite) to remove heavy metals, including Ni(II), Zn(II) and Ca(II). A magnetic composite resin, called phenol-sulphonic formaldehyde-iron ferrite, has been investigated in the removal of Co(II) from aqueous solution (Kim and Lee, 2001). It was documented that, at given experimental conditions, the maximum sorption capacity of the composite resin for Co(II) species is in excess of 3.1meq/g resin.

Detailed research by Ebner *et al.* (2001) on the use of magnetite and magnetite-silica composite for the adsorption of Cs(I), Sr(II) and Co(II) from aqueous solutions has been reported. In a project carried out by Slovakian researchers, nano-scale magnetite particles were investigated with respect to their adsorption of heavy metal ions such as Pb(II), Cu(II) and Cd(II), from aqueous media (Vaclavikova *et al.*, 2003). The results are quite impressive and the sorption capacities for Pb(II), Cu(II) and Cd(II) are 54 mg/g, 15 mg/g and 65mg/g of sorbent, respectively. The use of polymer-coated magnetite particles to remove heavy metals such as Cu(II), Cr(III), Zn(II) and Ni(II) from water has also been documented (Phanapavudhikul *et al.*, 2003). Karapinar (2003) has also investigated the removal of ferrihydrite from wastewater, using magnetic seeding (magnetite as a seeding material) and high-gradient magnetic separation. More recently, Ambashta *et al.* (2003) have reported the preparation and use of nano-scale magnetic particles in the removal of Cs(I) from radioactive wastes. This sorbent consists of hexacyanoferrate (II)-loaded magnetite particles, with a particle size range of 8 to 30 nm. The use of magnetite in the removal of heavy metals, including Pb(II), Cd(II) and

Mn(II) from water has also been studied, and this invention has been patented (Prenger *et al.*, 2003). The removal of dissolved organic carbon (DOC) such as humic and fulvic acids by a magnetic iron exchange resin has also been reported (Nguyen *et al.*, 2003).

In recent years a research group comprising scientists in Brazil and Argentina (Oliveira *et al.*, 2002; 2003; 2004) has carried out extensive studies on the use of MPT in environmental remediation. They have tested different magnetic composites in the removal of water pollutants, including heavy metals, organic substances and oil spills. These composites are made by using adsorbents such as clay or activated carbon in combination with iron oxides. The ratio of adsorbent and iron oxide can be 1:1; 1.5:1; 2:1, depending on the quantity of adsorbing material used. More recently, an investigation into the use of nano-scale magnetite particles in the removal of Cr(VI) from aqueous media was carried out (Hu *et al.*, 2004). A magnetic material, $MnFe_2O_4$ has also been tested to adsorb water-soluble azodyes (Wu and Qu, 2005). It was reported from this study that the maximum adsorption capacity for this contaminant is 53.8 mg/g sorbent. Magnetite and the effect of its particle size on the adsorption and desorption of arsenite and arsenate has been reported (Yean *et al.*, 2005). A variety of environmental applications of MPT can be found in a review by Ngomsik *et al.* (2005).

1.6.2 The application of magnetic particle technology to oil spill remediation

Although magnetic materials and MPT has been used extensively in some areas of environmental remediation, *vide supra*, only a limited number of studies have been specifically carried out on oil spill remediation.

One of the earliest studies involved the use of ferromagnetic sorbents for oil spill recovery and control (Turbeville, 1973). The ferromagnetic sorbent is iron coated with polystyrene. The bead has a particle size ranging from 3 to 5 mm in diameter. A prototype floating grid of these magnetic beads was also made and tested with respect to oil recovery. Such MPT has shown considerable promise as evidenced by subsequent studies by Godinho (1993), Orbell *et al.* (1997). An investigation into the use of magnetite and maghemite to the removal of oil spills from a water bath has been carried out (Chun and Park, 2001). It was reported that these particles could remove up to 80%

oil. In addition, they were effective at removing dispersants that are used to disperse the oil spill, thus resulting in a removal of ca. 100% when used in conjunction with the dispersant. Magnetic filtration technology has been employed to remove petrochemicals such as a decane/water solution and to remediate oil spills (Apblett *et al.*, 2001). The magnetic extractants used are activated carbon/magnetite, nickel ferrite composites, polymer-coated iron, iron oxide powders and poly(dimethylsiloxane)-coated hematite, the latter having the highest affinity for oil.

A magnetic copolymer, CleanMag^{TM}, has been invented by Nikolaidis (1997). It was reported that this magnetic, porous and oleophillic material could sorb 100% oil. Also in recent years, another oil spill sorbent based on magnetic particles has been produced (Christodoulou, 2002), named EcoMag^{TM}. It has also been documented to have the potential of removing up to 100% of an oil spill. This product is different from the CleanMag^{TM} (a co-polymer *organic* product) in that this sorbent is made from *inorganic* materials; therefore, it can tolerate very high temperatures, up to 800 ^{o}C. Recently, scientists in Kazakhstan have invented a new sorbent that can remove 98% of an oil spill. This magnetic substance contains at least 30% of zero valent iron (RSNA, 2004). Oliveira and his team (2004) have also investigated the application of magnetic composites to oil spill remediation. This study, although not quantified, does show promise. More recently, Li *et al.* (2004) have also reported the successful application of a magnetic composite resin that shows a removal 100% oil from a water bath. A polymer coated vermiculite – iron composite has been tested as a magnetic adsorbent for the removal of oil from water (Machado *et al*., 2006).

In more recent developments, an investigation into the manufacture of a magnetic oil sorbent material consisting of a composite of iron powder and a highly adsorbent plastic polymer has been initiated between Victoria University and RFP Manufacturing P/L and the associated Recoverit Pty. Ltd. (http://www.recoverit.biz) Australia. The preliminary experimental results show that this substance is very effective at removing oil slicks, showing a removal of ca. 100% for a number of crude oils.

It is clear from the above studies that the use of magnetic materials in oil spill treatment has a number of potential advantages.

1.6.3 The application of magnetic particle technology to cleansing oiled wildlife

Although the application of MPT to environmental remediation (in general) and to oil spill remediation (in particular) has been extensively investigated, this is not the case with respect to its application to the removal of oil contamination from wildlife, including birds. This area has been almost exclusively confined to the work of researchers at Victoria University in collaboration with researchers at the Phillip Island Nature Park, Victoria, Australia. (Orbell *et al.*, 99; 2004; Ngeh, 2002). This technology, using finely divided iron powder as a non-toxic, non irritating cleansing agent, promises a number of advantages over conventional detergent-based methods in terms of time, labour and cost - as well as being less stressful to the bird.

1.7 Significance of the research

Even a small residual of oil on plumage can have deleterious effects - not just in term of toxicity and feather damage (with associated reduced water-proofing, loss of heat insulation and buoyancy), but also with respect to the contamination of eggs and chicks (Burger, 2003). Thus, the removal of 100% of all types of contaminant from feathers is considered to be an important objective. Indeed one of the significant objectives of the present work is to demonstrate that MPT has the potential of achieving 100% oil removal from feathers.

In addition, the problem of tarry and/or very viscous oil contamination of wildlife is not uncommon (Berkner *et al.*, 1977; Holcomb and Russell, 1999) and this presents additional challenges to rescuers and rehabilitators (OWCN, 1999; OWCN-a, 2003; USFWS, 2002). Indeed, although MPT had been demonstrated to be effective at removing a variety of non-tarry oils and their corresponding emulsions from feathers (Orbell *et al.*, 1999; 2004; Dao *et al*., 2006), it was suggested (Copley, 1999; Hill, 1999) that tarry or highly viscous oil contamination might prove resistant to the application of the so-called ‘magnetic cleansing’ method. An objective of this project is to demonstrate that MPT can indeed be effective at removing this kind of contamination.

Another challenge in oiled wildlife rehabilitation is the removal of weathered oil from fur or feathers (OWCN, 1999; OWCN-a, 2003; OWCN-b, 2003; Bryndza, 2005). The common technique for cleaning of this kind of contaminant involves the use of warm water, detergent and pre-treatment agents (pre-conditioners) (OWCN, 1999; OWCN-a, 2003; OWCN-b, 2003; USFWS, 2002; Miller & Bryndza, 2005). Therefore, an investigation into the application of MPT, in conjunction pre-conditioners, to the removal of various weathered contaminants from feathers will be undertaken.

Although a number of pre-conditioners have been reported as being useful in the cleaning of weathered oil from feathers, their effectiveness is not quantified and is mainly anecdotal and based on observation alone (USFWS; 2002; Gregory, 2006). Thus, a method based on MPT to quantify the relative efficiency of various pre-conditioners will be developed.

In the research described herein the following definitions have been adopted. "Fresh" oil is non-tarry (liquid) oil that has not been weathered. "Tarry" oil is oil that is extremely viscous and can be solid under ambient conditions. "Weathered" oil is tarry or non-tarry oil that has been exposed to the environment for up to 14 days. Note that these terms have been used elsewhere *albeit* defined slightly differently in some cases (Berkner *et al.*, 1977; Monfils *et al.*, 2000; NOAA; 2000; Moles *et al.*, 2002; Perkins *et al.*, 2003).

1.8 Objectives of the research

The objectives of this research are presented as follows:

- To complete a detailed investigation into the effects of the physical characteristics of different grades of iron powder on contaminant removal.
- To identify an optimal grade of iron powder capable of achieving ca. 100% contaminant removal from feathers and plumage.
- To investigate the potential of MPT to remove tarry contamination from feathers and plumage and to investigate the physical chemistry of this process.
- To investigate the effect of weathering on the efficacy of contaminant removal by MPT.
- To investigate the role of pre-conditioners when used in conjunction with MPT.
- To develop a convenient *in vitro* magnetic cleansing methodology for the screening of pre-conditioning agents for use by either magnetic cleansing or traditional detergent-based methods.

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CHAPTER 2: METHODOLOGIES FOR THE INVESTIGATION OF OIL REMEDIATION USING MAGNETIC PARTICLES

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2.1 Methodology for gravimetric determination of oil removal

An existing gravimetric method, developed by Orbell *et al*. (1997; 1999), was employed in this research in order to determine the magnetic removal of a contaminant from a given substrate, including inorganic (glass) and organic (feathers) substrates. It is described as follows:

2.1.1 Glass substrate

A pre-weighed (w_1) petri dish was charged with a fixed mass of a contaminant and was then re-weighed (w_2). A mass of magnetic particles was applied to the contaminant and the petri dish was then re-weighed (w_3). The particle-to-contaminant ratio, R, is defined as the mass of particles divided by the mass of contaminant of interest, and R may be calculated according to Equation 2.1:

$$R = (w_3 - w_2)/(w_2 - w_1) \qquad (2.1)$$

The contaminant and magnetic particles were mixed well and left for one minute to ensure sorption. It was demonstrated in previous experiments (Godinho, 1993) that the adsorption is almost instantaneous. A magnetic tester was used to harvest the contaminant-laden magnetic particles. The petri dish was then re-weighed (w_4). The percentage of contaminant removal, P (%), can be determined using Equation 2.2:

$$P\ (\%) = [(w_2 - w_4)/(w_2 - w_1)] \times 100\% \qquad (2.2)$$

The harvesting process was repeated until a constant value of P (%) was achieved. The maximum value of P (%) is designated as P_o (%). The value P_o (%) is achieved at a specific R-ratio designated R_o. A sample calculation using Equations (2.1) and (2.2) is presented in Appendix 2.

2.1.2 Feather clusters

A number of feathers (usually four) were tied into a cluster and weighed (f_1). The feather cluster was then dipped into a 100 mL beaker of a contaminant to achieve saturation. The cluster was allowed to drain on a tarred petri dish for 10 min prior to being re-weighed (f_2). The cluster was then removed from the dish and the residual quantity, r, was recorded. Hence, the weight of the contaminant-laden feathers, f_3, for further experimentation is given by:

$$f_3 = f_2 - r \qquad (2.3)$$

The contaminated feathers were then completely covered with magnetic particles in order for absorption and adsorption of the contaminant to occur. At least a minute is provided for this process although previous study has indicated that it is almost instantaneous (Godinho, 1993). The contaminant-laden magnetic particles were then harvested from the feathers using a magnetic tester. The stripped feather cluster was then re-weighed (f_4). The percentage removal of the contaminant, F (%), was calculated using Equation 2.4

$$F\ (\%) = [(f_3 - f_4)/(f_3 - f_1)] \times 100\% \qquad (2.4)$$

A number of applications (N) were performed until a constant value of F (%) was achieved. A sample calculation using Equations (2.3) and (2.4) is presented in Appendix 2.

2.1.3 Whole bird model (carcass)

A method for the gravimetric determination of contaminant removal from a bird carcass has been developed previously (Ngeh, 2002). This method was adapted for this research and is described as follows:

A bird (carcass) was weighed (p_1) using a top loading balance. An amount of oil was carefully poured onto the plumage (breast/contour feathers) and the carcass was then re-weighed (p_2). Iron powder was then applied to the feathers and the carcass was left for about 1.5 min to allow the absorption and adsorption of contaminants to occur. The oil-laden iron powder was then removed using a magnetic tester and the carcass was re-weighed (p_3). The percentage of oil removed C (%) from the carcass is determined according to Equation (2.5)

$$C\ (\%) = [(p_2 - p_3) / (p_2 - p_1)] \times 100\% \qquad (2.5)$$

Generally, it takes approximately 35 - 40 minutes to carefully carry out 10 treatments of magnetic cleansing for an oiled bird carcass.
It is also worth noting that oil-laden iron powder can be recycled using solvent extraction (Ngeh, 2002) or centrifuge (Unpublished data).

2.2 Materials and equipment

2.2.1 Materials

The following materials were used in the research:

2.2.1.1 Iron powders

Eight different types of iron powder varying in particle size distribution, particle structure (shape) and surface texture were supplied by Höganäs AB (Höganäs AB, 2003), Fig. 2.1. The eight different grades and their descriptions are listed in Table 2.1

Figure 2.1: The iron powder used in the experiments.

Table 2.1: The grades of iron powder used in the experiments.

Grade	Physical characteristics			Chemical characteristics			
	Grades of iron powder	Average particle size (μm)	Specific surface BET (m^2/kg)	Fe total (%)	Fe metallic (%)	C (%)	S (%)
1	A40S atomised unannealed coarse	274	100	98.0	97	0.41	0.01
2	M40 spongy unannealed coarse	185	110	98.5	97	0.19	0.007
3	A100S atomised unannealed fine	80	120	98.0	97	0.410	0.008
4	C100.29 spongy unannealed fine	93	115	98.5	97	0.220	0.006
5	ASC100.29 atomised annealed fine	89	90	99.5	99.3	0.003	0.008
6	NC100.24 spongy annealed fine	100	95	99.0	98.5	0.005	0.005
7	ASC300 atomised annealed superfine	36	100	99.5	99.1	0.003	0.01
8	MH300.29 spongy annealed superfine	37	100	99.0	98.5	0.010	0.006

2.2.1.2 Contaminants

Seven types of oil and two emulsions have been used in the experiments, Fig. 2.2. These are supplied from different providers, including Exxon/Mobil Oil Pty. Ltd., Shell Ltd, and IBS (International Bunker Supplies) Pty. Ltd, Valvoline Pty. Ltd, Australia. The emulsions were made from crude oil and seawater (50% v/v) according to the method described by Bassères *et al*. (1994). A fixed volume of seawater (e.g. 30 mL) and the same volume of contaminant were mixed in a 100 mL beaker. The mixture was then stirred for 6 h to create an emulsion ready for immediate use. All samples were unweathered.

The characteristics of these contaminants, provided by the suppliers, are given in Table 2.2. However, the viscosity of the oils was double-checked in the laboratory since viscosity plays an important role in oil removal (to be discussed later in the subsequent Chapters). At first, a rapid method using a rotating spindle viscometer (Brookfield Synchro-Lectric viscometer) was chosen to measure the dynamic viscosity of the oils and emulsions. However, this instrument worked well only with the Arab medium crude oil (AO), showing a viscosity of 57 cps. The other oils could not be measured using this method, as their viscosities were too low. An attempt was also made to measure the viscosity of the emulsions. However, the readings were variable. This could be explained by the heterogeneity of the emulsion. It was finally decided that the viscosity of the emulsions could not be accurately determined.

An alternative method for measuring the viscosities of the oils was subsequently employed, namely, using a capillary tube viscometer, Ostwald's method (Findlay and Kitchener, 1954). In this method, cyclohexane is used to calibrate the viscometer. The viscosity of each oil was measured two or three times, depending on time constraints. Due to the very long time to conduct one reading for heavy oils such as engine oil (EO) and Arab medium crude (AO), two measurements only were made in these cases. For lighter oils such as Gippsland crude (GO) and Merinie crude (GO), three measurements were carried out. The average viscosity values are listed in Table 2.2. All the measurements were conducted at room temperature. For another three oils namely, bunker oil 1 (BO1) (used for fresh oil experiments), bunker oil 2 (BO2) (used for weathered oil experiments) and Shell crude oil (SO), measurements were not conducted as their viscosity values were provided by the suppliers.

Figure 2.2: The crude oils used in the experiments.

2.2.1.3 Feathers

Feather clusters from duck and penguin were used for all experimentation. Breast/contour feathers were obtained from the Mallard Duck (*Anas platyrhynchos*, body weight range: 2.2 - 2.6 kg) and from the Little Penguin (*Eudyptula minor*, body weight range: 0.42 - 1.88 kg). The former animals were obtained from a local market, and the latter were provided by the Phillip Island Nature Park, Australia. Apart from feather clusters, the Little Penguin (*Eudyptula minor*) carcasses were also employed for the whole bird model experiments. These penguins were the victims of predator attacks (usually foxes) and traffic accidents (Healy, *personal communication*, 2004).

Table 2.2: The various contaminants employed in the experiments.

	Contaminant used	Geographical origin	Date sample obtained	Supplier	Specific gravity (at 15^{o}C)	Viscosity (cSt)	Pour point (^{o}C)
1	Merinie crude oil (MO)	Saudi Arabia	15/05/99	Exxon/Mobil Oil Pty. Ltd., Australia	0.85	4.1 (at 22 ^{o}C)	-42
2	Arab medium crude oil (AO)	Saudi Arabia	15/05/99	Exxon/Mobil Oil Pty. Ltd., Australia	0.89	50.1 (at 22 ^{o}C)	-10
3	Gippsland crude oil (GO)	Australia	10/05/03	Exxon/Mobil Oil Pty. Ltd., Australia	0.79	1.4 (at 22 ^{o}C)	<-42
4	Bunker oil 1 (BO1)	Australia	15/05/04	IBS Australia	0.95	180 (at 40 ^{o}C)	
5	Bunker oil 2 (BO2)	Australia	08/05/04	IBS Australia	0.97	222 (at 40 ^{o}C)	
6	Engine oil (Mobil Super XHP 20W-50) (EO)	Australia	05/09/99	Valvoline Pty. Ltd., Australia	0.90	307.13 (at 22 ^{o}C)	-24
7	Shell crude oil (SO)	Australia	10/02/04	Shell Ltd. Australia	0.7-1	3000-4000 (at 100 ^{o}C)	26-29^{o}C
8	(Gippsland crude oil /seawater) emulsion (ES1)						
9	(Engine oil/seawater) emulsion (ES2)						

2.2.1.4 Pre-treatment (pre-conditioning) agents

A variety of pre-conditioning agents were used in the research. These include olive oil, Canola oil, blended oil (canola/soybean), de-oiler (BD1) that is used in the Southern African Foundation for the Conservation of Coastal Birds-SANCCOB (*sic*), methyl oleate, and Bio-dispersol. The first three are commercially available and can be purchased at any supermarket. The last two, methyl oleate and “Bio-dispersol”, were kindly provided by VicChem Ltd., Australia.

2.2.2 Equipment

The equipment required for this research includes: a Laboratory Magnetic Tester (Alpha Magnetics, Victoria, Australia), as shown Fig. 2.3. The magnet within the tester is a “rare earth magnet” comprised of iron, boron and neodymium. This device is designed so that the magnetic field can be switched off and on mechanically by moving the plunger up or down, respectively.

Figure 2.3: Laboratory Magnetic tester for harvesting contaminant-laden magnetic particles.

A top loading balance, model AC-4K (Denver Instrument Company), accurate to two decimal places, was used for gravimetric measurements on the carcasses. An analytical balance, Galaxy ™ 160 (Australian Instrument Services-AIS), accurate to four decimal places, was employed for gravimetric measurements on the feather clusters.

An oven was used for the drying of carcasses. A scanning electron microscope (Phillips Electronics, Eindhoven, the Netherlands, Model XL30-FESEM) was used to take micrographs of the iron powder.

2.3 Presentation of the experimental data

Since there are two different kinds of oil removal experiment utilized in this thesis; namely the removal of oil as a function of ***(i)*** the particle to oil ratio and of ***(ii)*** the number of treatments, the following section describes how the experimental data for each is presented in order to extract the maximum possible information.

2.3.1 Sorption "Isotherm"

2.3.1.1 Removal from a glass substrate

A typical isotherm for the sorption of a contaminant from a glass matrix (glass petri dish surface) is shown in Fig. 2.4. In this plot, P (%) is the percentage pick-up by weight of contaminant, whilst R is the particle-to-contaminant ratio by weight. Whenever possible all experiments were performed in five-fold replicate and standard errors (SE) or 95% confidence intervals are shown as error bars. The equations for the error analysis are presented in a sample calculation in Appendix 2. As can be seen from Fig. 2.4, the contaminant pick-up eventually reaches a plateau defined by P_o (%) and R_o (Section 2.1.1). These values are unique for a particular contaminant and magnetic particle grade. It may be observed that, as a general rule, the reproducibility of pick-up increases as the optimum values of P (%) and R are reached.

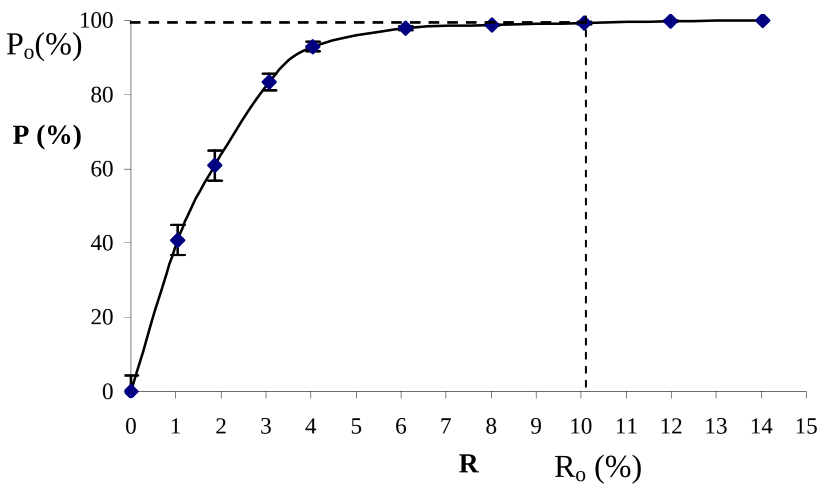

Figure 2.4: Characteristic sorption isotherm for oil pick-up from a glass matrix. The contaminant is Arab medium oil and the iron powder is the optimal iron powder grade, MH300.29. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 2 in Appendix 2.

2.3.1.2 Removal from feather clusters

A typical isotherm for the sorption of contaminant from a feather cluster is shown in Fig. 2.5. The parameter F (%) is the percentage pick-up by of contaminant by weight and N is the number of treatments. Error bars represent 95% confidence intervals for five replicates.

As can be seen from Fig. 2.5, the contaminant pick-up eventually reaches a plateau after a certain number of treatments. As with pick-up from a glass surface, the reproducibility increases as the optimum pick-up is approached.

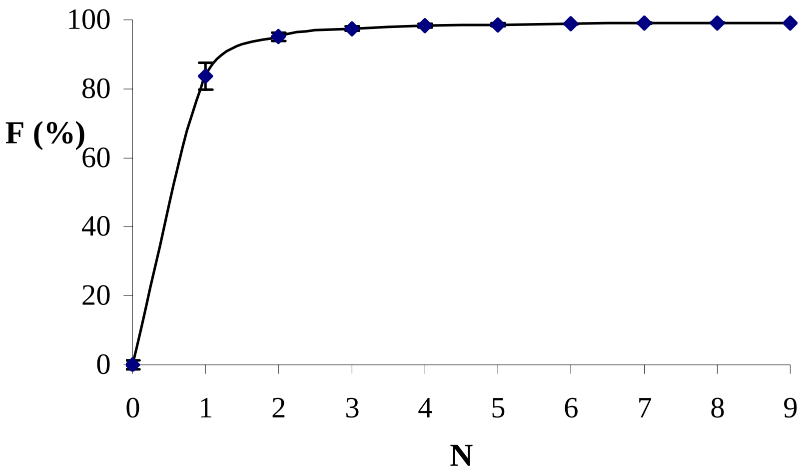

Figure 2.5: Characteristic sorption isotherm for oil pick-up from a feather cluster. The contaminant is Arab medium oil and the iron powder is M40 grade. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 3 in Appendix 2.

2.3.1.3 Removal from plumage (carcass)

A typical isotherm for the sorption of contaminant from plumage is presented in Fig. 2.6. The parameter C (%) is the percentage pick-up of contaminant (by weight) and N is the number of treatments.

It can be seen from Fig. 2.6 that the contaminant removal from plumage achieves its maximum more gradually than for removal from a glass surface or from a feather cluster. This is, perhaps, to be expected although a plateau is achieved after approximately the same number of treatments. Again, reproducibility increases as the optimum pick-up is approached.

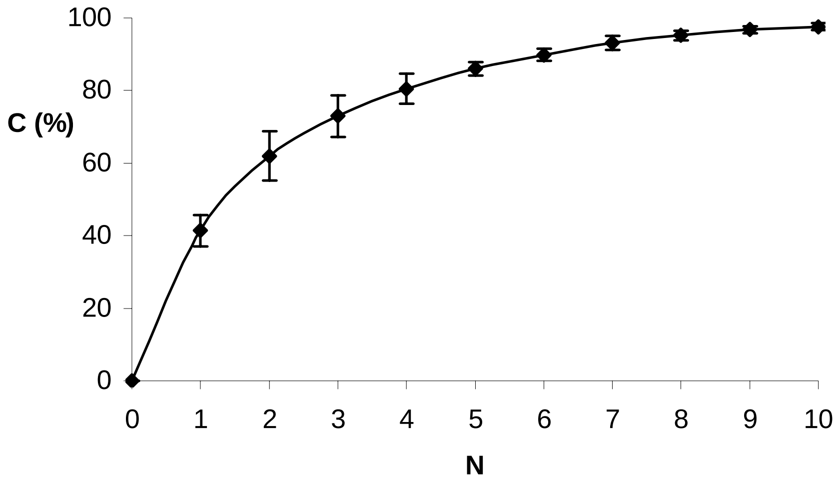

Figure 2.6: Characteristic sorption isotherm of oil pick-up from plumage. The contaminant is Gippsland oil and the iron powder is MH300.29 grade. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 4 in Appendix 2.

2.3.2 Comparative histograms

An alternative way of presenting the data for oil pick-up from feather clusters and from plumage, since the abscissa values are necessarily integers, is by comparative histograms. This can be particularly useful when multiple sets of data need to be compared. A typical example of this kind of representation is shown in Fig. 2.7 where the isotherms for pick-up from duck and penguin feathers are compared. The use of histograms for pick-up from a glass substrate is not appropriate since the abscissa values are non-integers.

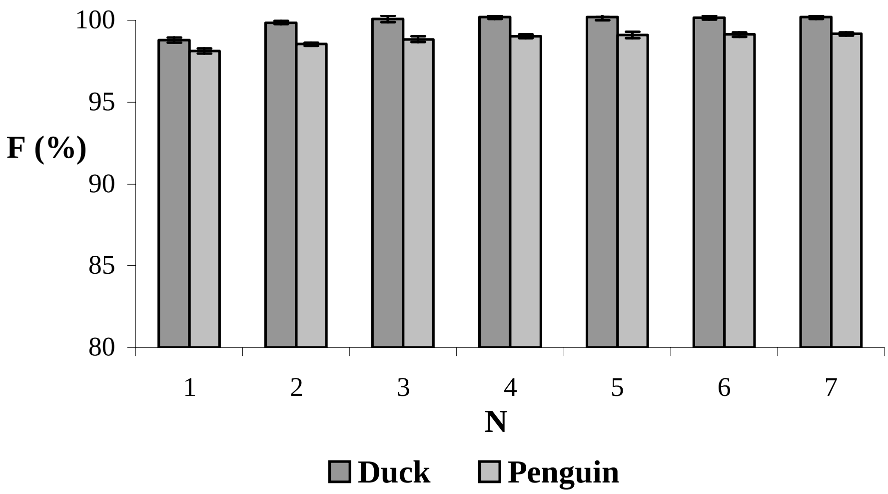

Figure 2.7: Comparative histograms of contaminant pick-up for duck and penguin feather clusters. Error bars represent the 95% confidence intervals for five replicates. The data is presented in Table 5 in Appendix 2.

2.4 References

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CHAPTER 3: THE CHARACTERISATION OF MAGNETIC PARTICLE TYPE (GRADE) WITH RESPECT TO OIL PICK-UP

CHAPTER 3: THE CHARACTERISATION OF MAGNETIC PARTICLE TYPE (GRADE) WITH RESPECT TO OIL PICK-UP

3.1 Introduction

The physical properties of sorbents including particle size, particle shape (structure) and surface texture play an important role in oil removal or sorption, and the effect of these has been documented (Johnson *et al.*, 1973; Choi and Cloud, 1992; Ribeiro *et al.*, 2000; Toyoda *et al.*, 2002; Asien *et al.*, 2003; Radetic *et al.*, 2003; Roulia *et al.*, 2003; Saito *et al.*, 2003; Sayed *et al.*, 2004). Regarding the use of magnetic particles in environmental remediation, it has been suggested from previous studies that contaminant sorption is influenced by properties such as particle size (Oliveira *et al.*, 2002; Ngomsik *et al.*, 2005; Yean *et al.*, 2005; Wu and Qu; 2005), particle shape (structure) (Chun and Park, 2001; Ebner *et al.*, 2001; Ngomsik *et al.*, 2005; Wu and Xu, 2005; Wu and Qu, 2005), and surface texture (Phanapavudhikul *et al.*, 2003). With regard to the use of magnetic particles (magnetite and maghemite) in oil remediation, it was reported that the sorption of oil dispersants was affected by the shape of the particles (Chun and Park, 2001). More recently, it was suggested that oil removal could be improved by manipulating the properties of magnetic particles (Ngeh, 2002). In this regard, a number of iron powders, and the physical and chemical characteristic of these, as described by the manufacturer (Höganäs AB Products Booklet, 2003) and given in Table 2.1, have been tested. The variation in chemical composition between these powders is very small and is not expected to have an influence on the oil sequestering properties. However, the various physical characteristics of the particles are expected to have significant effects on oil removal. Therefore eight different iron powder grades were selected with various particle size distributions, particle shapes (or structures) and surface textures in mind. For each of these eight grades of iron powder the efficacy of removal of a 'representative' oil from a glass surface (petri dish) and from feathers has been assessed. It has been assumed (since the experimental work involved is very labour intensive and time consuming) that the results for this oil will be broadly reflective of most oil types. The oil selected is Arab medium crude oil (AO) since it is classified as a medium crude with a kinematic viscosity of 50.10 cSt (Table 2.2). It also has a dark appearance, making the process of removal easier to track visually.

The purpose of these experiments is to justify the hypothesis that the efficacy of oil removal can be manipulated by altering the above characteristics and, subsequently, to identify an (improved) optimal particle type for further studies. In particular, these experiments were designed to pursue the important proof of principle that 100% removal (within experimental error) is achievable. It must be taken into consideration that the nature of the matrix also has an effect on contaminant removal (Ngeh, 2002). Therefore, the characterisation of particle type has been carried out for removal from both a glass surface and from feathers. All experiments were conducted in five-fold replicate and at a room temperature of ca. 293 K, unless otherwise stated.

3.2 Characterisation of oil pick-up from a glass substrate

The methodology for oil removal from a petri dish has been described in Section 2.1.1.1. In accordance with Section 2.3.1.1, the oil pick-up, P (%), is mapped against the particle-to-oil ratio, R.

3.2.1 The effect of particle size distribution

It has been suggested that particle size distribution has an important role to play with respect to environmental and chemical applications (Höganäs AB, 2003). This is also considered to be of relevance for the present work. Therefore, the oil removal efficacy via the magnetic cleansing technique has been compared between grades that have various particle size distributions. Given the fact that the grades are also different in particle shape (structure) and surface texture, some care has to be taken in the interpretation of the results. For this reason, the data have been divided into two categories for comparison purposes, namely “*atomised*” and “*spongy*”.

3.2.1.1 Atomised grades

Four atomised grades have been tested with regard to the pick-up of oil from a petri dish. The grades, in decreasing order of particle size are: coarse atomised un-annealed (A40S), fine atomised annealed (ASC100.29), fine atomised un-annealed (A100S) and superfine atomised annealed (ASC300). The average particle size for each of these grades is quantified in Table 3.1, and ranges from 36 – 274 μm.

Table 3.1: Atomised iron powder grades and their estimated particle size (Höganäs AB, 2003; 2004).

No	Atomised iron powder grade	Estimated average particle size (μm)
1	Coarse atomised un-annealed-A40S	274
2	Fine atomised un-annealed-A100S	80
3	Fine atomised annealed-ASC100.29	89
4	Superfine atomised annealed-ASC300	36

The results of the oil pick-up for these atomised iron powder grades are shown in Fig. 3.1.

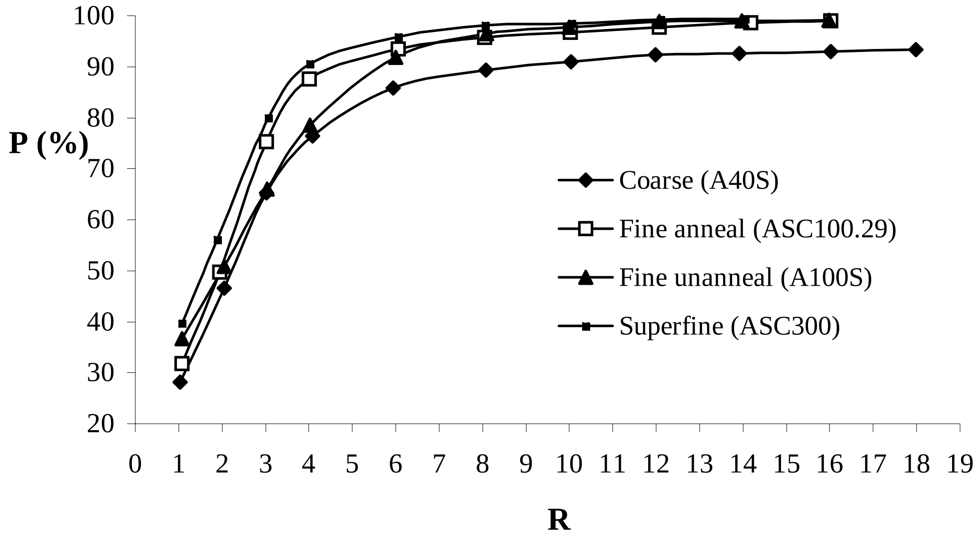

Figure 3.1: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, amongst different atomised grades. All experiments were carried out in five-fold replicate. Error bars (SE) have been omitted for clarity. The data are presented in Table 9 in Appendix 3.1.

For atomised iron powder grades, the results show that the oil pick-up increases as the particle size decreases. This can be explained by referring to the surface contact area of the particles. The smaller particles have a higher contact surface area, resulting in higher pick-up. The finding that the oil sorption increases as the particle size of sorbent decreases is similar to what is documented in the literature, using different sorbing materials and substrates (Oliveira *et al.*, 2002; Toyoda *et al.*, 2002; Aisen *et al.*, 2003; Roulia *et al.*, 2003; Sayed *et al.*, 2004; Yean *et al.*, 2005; Wu and Qu, 2005). In particular, the initial pick-up (defined by R = 1.0) is different for all grades, as shown in Fig. 3.2. However, the maximum removal is comparable for the fine and superfine grades, and is, within experimental error, greater than or equal to 99% - significantly higher than the corresponding pick-up of the coarse grade, Fig. 3.3. Overall, the superfine grade is found to be superior.

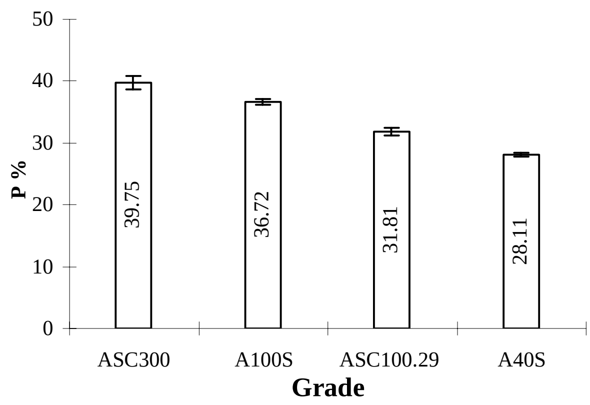

Figure 3.2: The initial oil pick-up from a petri dish for different atomised grades. Error bars represent the SE for five replicates.

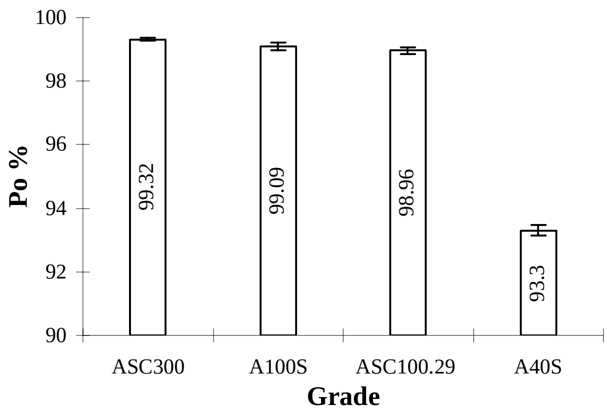

Figure 3.3: The maximum oil pick-up from a petri dish for different atomised grades. Error bars represent the SE for five replicates.

3.2.1.2 Spongy grades

Similarly, four spongy grades have been tested with regard to the pick-up of oil from a petri dish. The grades, in decreasing order of particle size are: coarse spongy un-annealed (M40S), fine spongy annealed (NC100.24), fine spongy un-annealed (C100.29) and superfine spongy annealed (MH300.29) (Höganäs AB, 2003). The average particle size for each of these grades is shown in Table 3.2, and ranges from 37 - 185 μm.

Table 3.2: Spongy iron powder grades and their estimated particle size (Höganäs AB, 2003; 2004).

No	Spongy iron powder grade	Estimated average particle size (μm)
1	Coarse spongy un-annealed-M40	185
2	Fine spongy un-annealed-C100.29	93
3	Fine spongy annealed-NC100.24	100
4	Superfine spongy annealed-MH300.29	37

The results of the oil pick-up for these spongy iron powder grades are shown in Fig. 3.4.

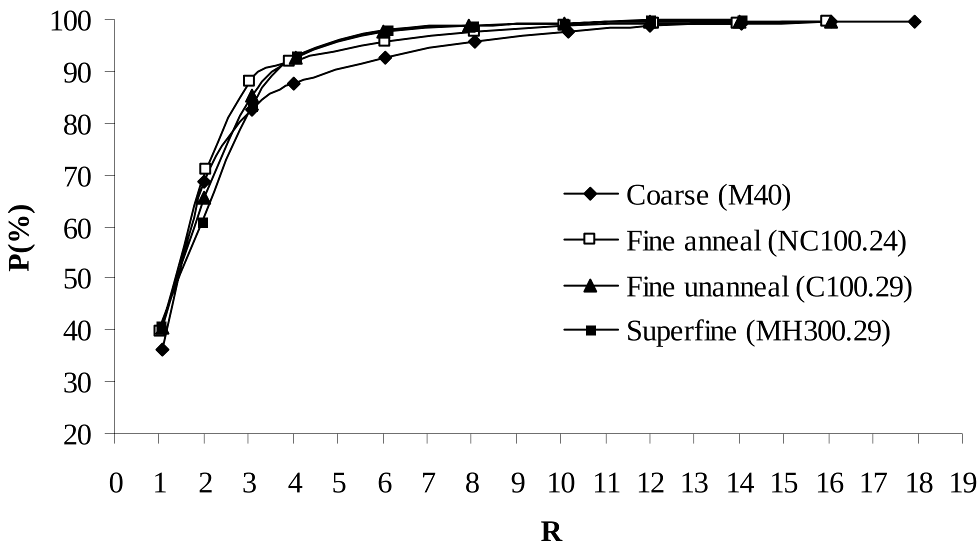

Figure 3.4: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, amongst different spongy grades. All experiments were carried out in five-fold replicate. Error bars (SE) have been omitted for clarity. The data are presented in Table 10 in Appendix 3.1.

For spongy iron powder grades, the results show that the oil pick-up tends to increase with decreasing particle size of the grades, although this effect is not as pronounced as compared to the atomised grades. In particular, the initial removal is lower for the coarse grade, M40, than for the other three grades (at the SE level), Fig. 3.5. However, the maximum pick-up is comparable for all grades and is, within experimental error, greater than 99.3%, Fig. 3.6. Again, the superfine grade is found to be superior overall.

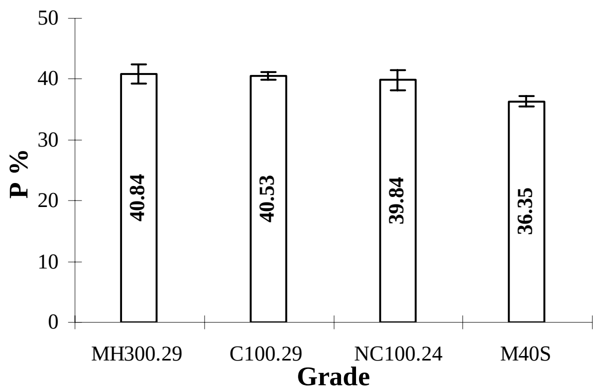

Figure 3.5: The initial oil pick-up from a petri dish for different spongy grades. Error bars represent the SE for five replicates.

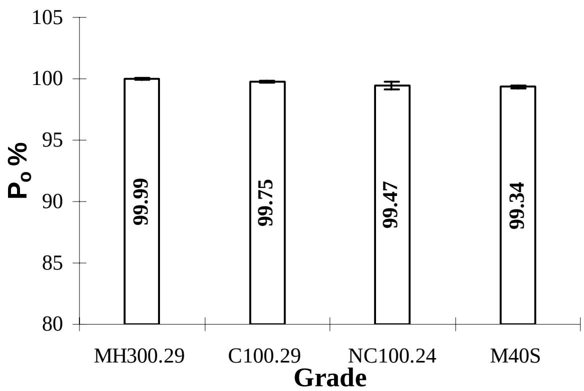

Figure 3.6: The maximum oil pick-up from petri dish for different spongy grades. Error bars represent the SE for five replicates.

Fig. 3.7 illustrates the influence of particle size distribution on the contaminant pick-up.

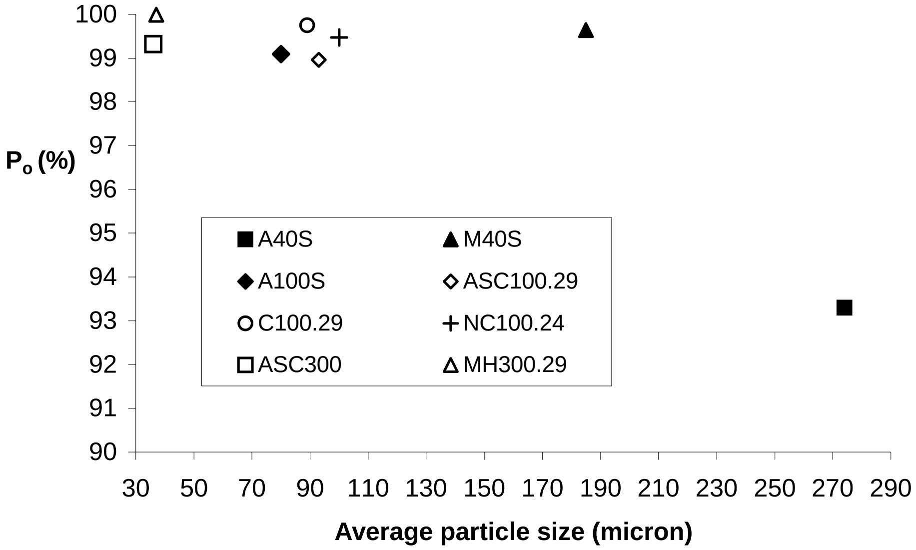

Figure 3.7: A plot of the percentage of maximum oil removed from a petri dish, P_o (%), versus the estimated average particle size for different particle grades. The data are presented in Table 11 in Appendix 3.1.

3.2.2 The effect of particle shape (structure) and surface texture

It is known that depending on the manufacturing process, the iron particles produced will vary in shape (structure) and surface texture. Such differences are characterised by the manufacturer as "atomised or spongy; annealed or un-annealed" (Höganäs AB, 2003). The manufacturing process can be briefly described in Fig. 3.8.

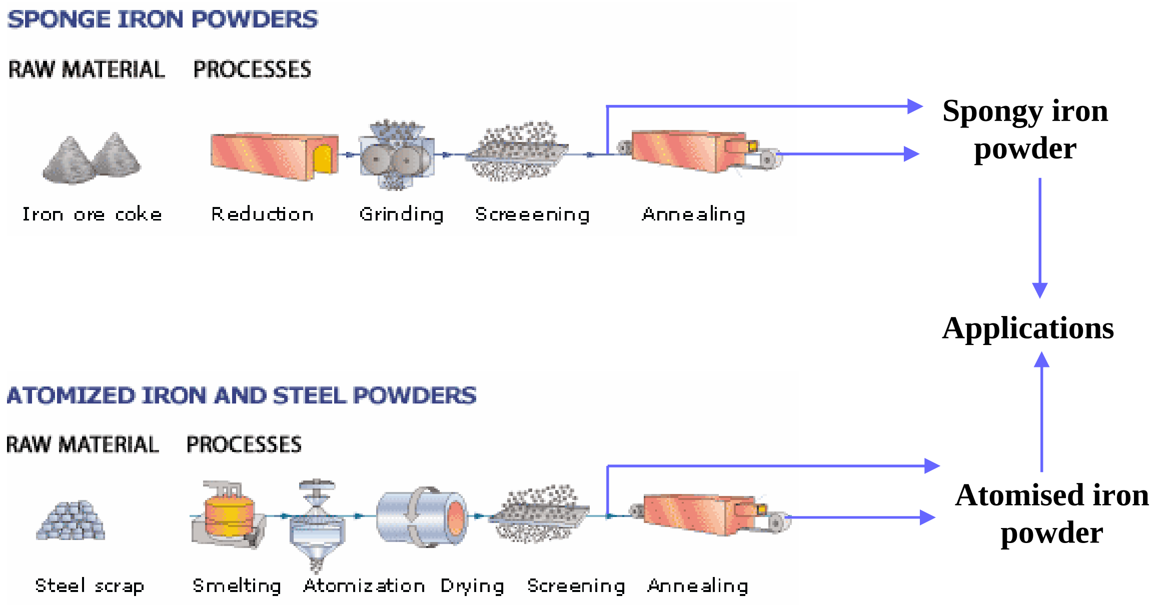

Figure 3.8: The manufacturing process of spongy and atomised iron powder (Modified from http://www.hoganas.com).

3.2.2.1 Atomised and spongy grades

It has been suggested that, together with particle size distribution, particle shape (structure) is also an important factor to consider when choosing particles for a particular application (Höganäs AB, 2003; Ngomsik *et al.*, 2005; Wu and Xu, 2005; Wu and Qu, 2005). As can be seen from Fig. 3.8, the atomised and the spongy grades are manufactured according to different processes. This results in their having different physical attributes. The difference between atomised/spongy and annealed/un-annealed is highlighted in the representative scanning electron micrographs from Figs. 3.9 to 3.16. Other micrographs of these particles at different magnifications are shown in Appendix 3.3.

The oil removal efficacy *via* the magnetic cleansing technique has been compared between different grades that have different structural (e.g. atomised versus spongy) and surface (e.g. annealed versus un-annealed) attributes. In order to ascertain the effect of “atomisation versus sponginess”, the oil pick-up isotherms of the following pairs of grades have been compared.

For reference, the scanning electron micrographs (SEM) of the relevant particles are shown in Figs. 3.9 - 3.16.

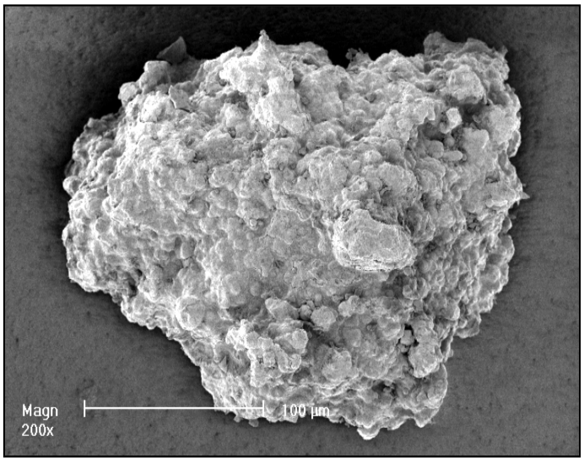

Figure 3.9: Scanning electron micrograph of *atomised* coarse un-annealed grade, A40S.

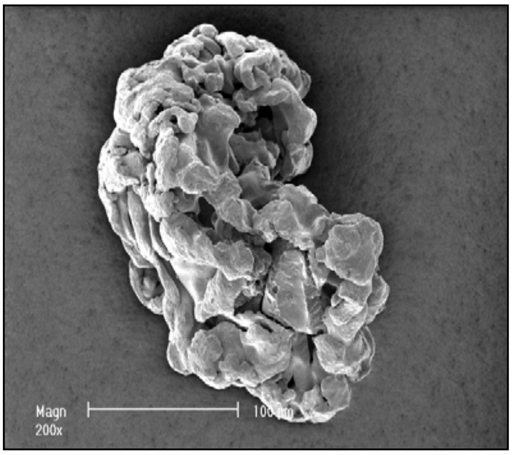

Figure 3.10: Scanning electron micrograph of *spongy* coarse un-annealed grade, M40.

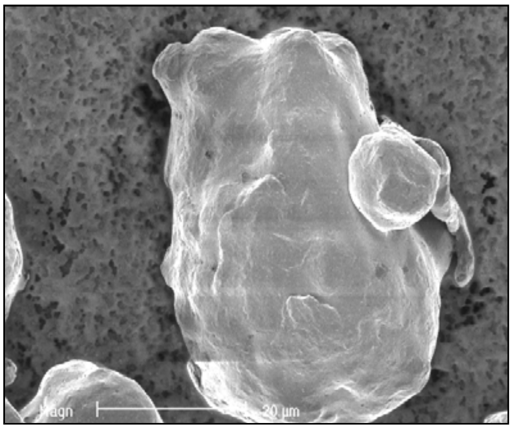

Figure 3.11: Scanning electron micrograph of *atomised* superfine annealed grade, ASC300.

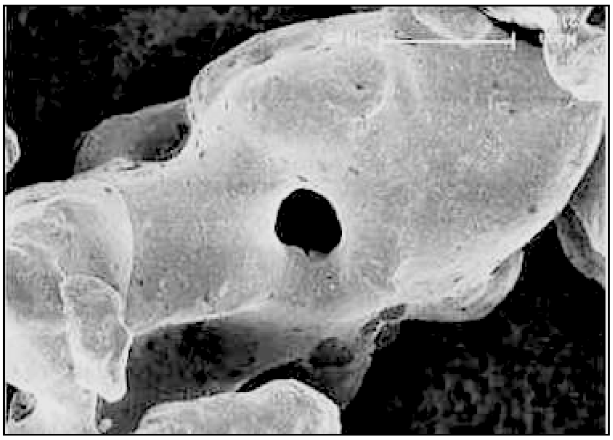

Figure 3.12: Scanning electron micrograph of *spongy* superfine annealed grade, MH300.29.

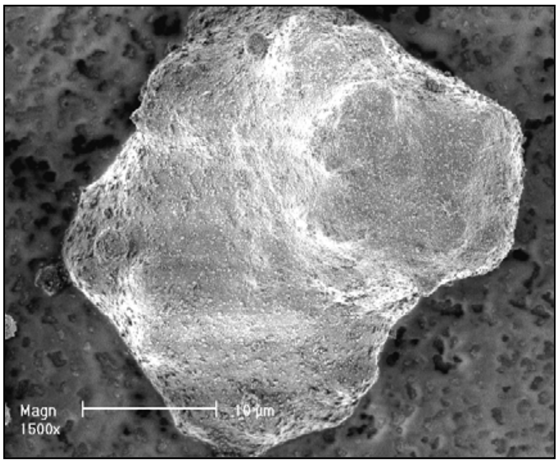

Figure 3.13: Scanning electron micrograph of *atomised* fine un-annealed grade, A100S.

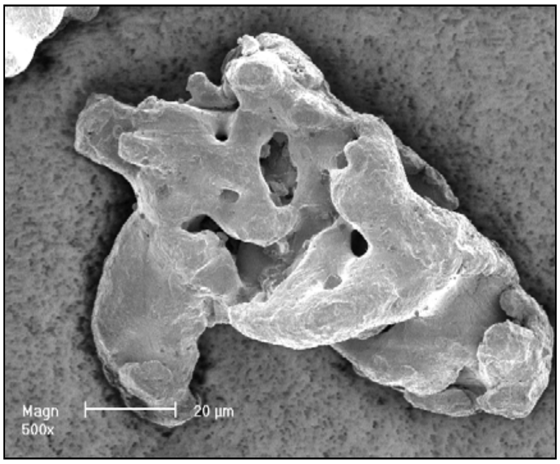

Figure 3.14: Scanning electron micrograph of *spongy* fine un-annealed grade, C100.29.

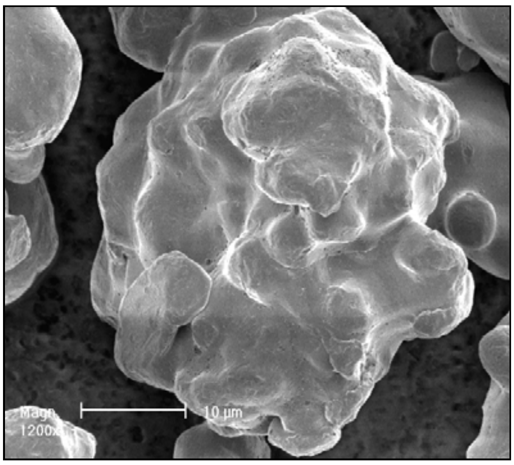

Figure 3.15: Scanning electron micrograph of *atomised* fine annealed grade, ASC100.29.

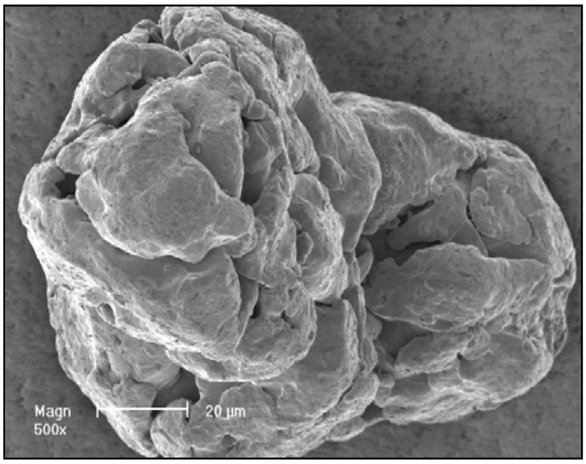

Figure 3.16: Scanning electron micrograph of *spongy* fine annealed grade, NC100.24.

(i) ***Coarse, un-annealed grades: A40S (atomised) versus M40 (spongy)***

As can be seen from Fig. 3.17, the removal is significantly lower for the atomised coarse un-annealed grade, A40S, than for the spongy coarse un-annealed grade, M40. Specifically, the initial pick-up of the atomised grade, A40S, is 28.11%, significantly lower than 36.35% of the spongy grade, M40. The maximum removal of the A40S is only 93.30%, significantly lower than 99.34% offered by the M40. The SEM micrographs of A40S and M40 are shown in Fig. 3.9 and Fig. 3.10, respectively.

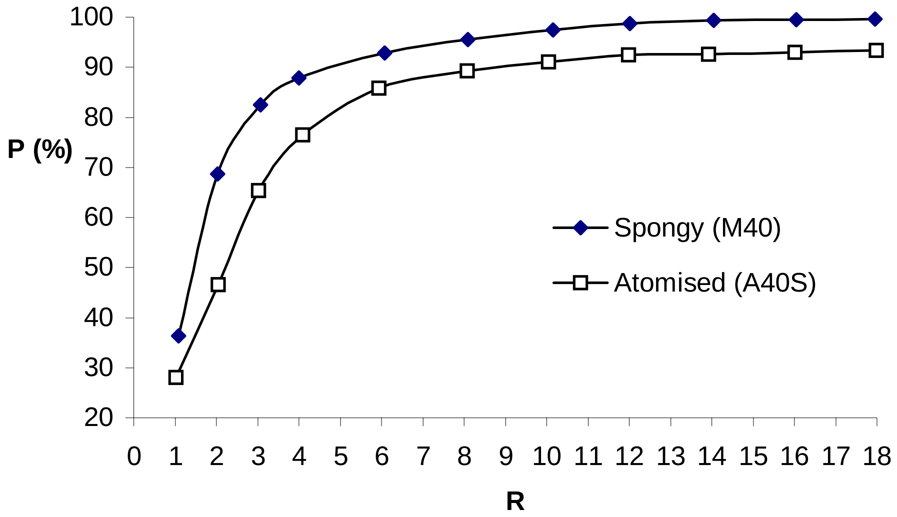

Figure 3.17: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, between atomised and spongy grades (*both coarse and un-annealed*). Error bars (SE) have been omitted for clarity. The data are presented in Table 12 in Appendix 3.1.

(ii) ***Fine, un-annealed grades: A100S (atomised) versus C100.29 (spongy)***

For the fine un-annealed grades, Fig. 3.18, the removal is significantly lower for the atomised fine un-annealed grade, A100S, than for the spongy fine un-annealed grade, C100.29. Specifically, the initial pick-up of the atomised grade, A100S, is 36.72%, significantly lower than 40.53% of the spongy grade, C100.29. The maximum removal of the A100S is only 99.09%, significantly lower (at the 95% interval confidence level) than 99.75% offered by the C100.29. The SEM micrographs of A100S and C100.29 are shown in Fig. 3.13 and Fig. 3.14, respectively.

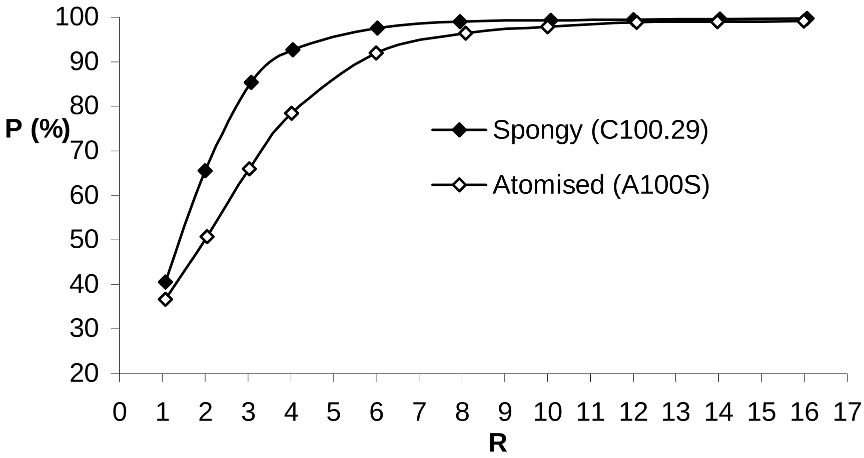

Figure 3.18: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, between atomised and spongy grades (*both fine and un-annealed*). Error bars (SE) have been omitted for clarity. The data are presented in Table 13 in Appendix 3.1.

(iii) Fine, annealed grades: ASC100.29 (atomised) versus NC100.24 (spongy)

For the fine annealed grades, Fig. 3.19, the removal is considerably lower for the atomised fine annealed grade, ASC100.29, than for the spongy fine annealed grade, NC100.24. Specifically, the initial pick-up of the atomised grade, ASC100.29, is 31.81%, significantly lower than 39.84% of the spongy grade, NC100.24. The maximum removal of the ASC100.29 is only 98.96%, considerably lower (at the SE level) than 99.47% offered by the NC100.24. Their SEM micrographs are shown in Fig. 3.15 and Fig. 3.16, respectively.

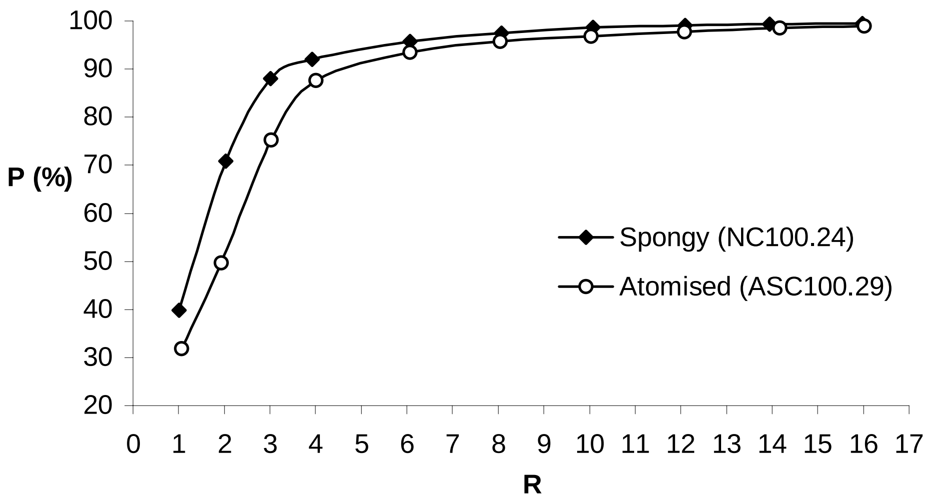

Figure 3.19: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, between atomised and spongy grades (*both fine and annealed*). Error bars (SE) have been omitted for clarity. The data are presented in Table 14 in Appendix 3.1.

(iv) Superfine, annealed grades: ASC300 (atomised) versus MH300.29 (spongy)

For the superfine annealed grades, Fig. 3.20, the initial removal is comparable for both the atomised superfine annealed grade, ASC300, and the spongy superfine annealed grade, MH300.29. However, the maximum removal for the atomised grade, ASC300, is 99.32%, significantly lower (at the 95% interval confidence level) than the 99.99% obtained for the spongy grade, MH300.29, Fig. 3.20. Thus the removal is lower for the atomised grade, ASC300, than for its respective spongy grade, MH300.29. The respective SEM micrographs of the ASC300 and MH300.29 are shown in Fig. 3.11 and Fig. 3.12.

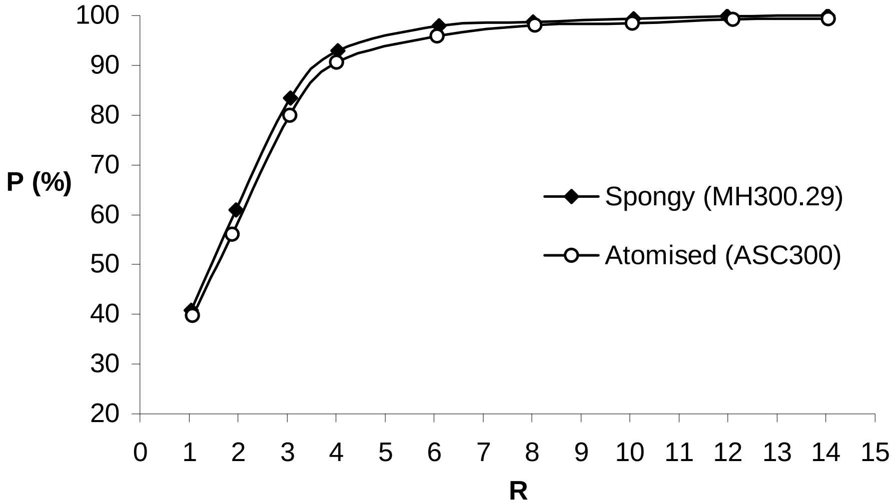

Figure 3.20: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, between atomised and spongy grades (*both superfine and annealed*). Error bars (SE) have been omitted for clarity. The data are presented in Table 15 in Appendix 3.1.

It can also be seen from Figs. 3.17 to 3.20 that for every single grade (coarse, fine or superfine) the oil pick-up of the atomised grades is lower than that of the respective spongy grades. It is noted, however, that the difference in oil removal between the atomised and spongy grades is more pronounced for the coarse grades than for the fine and superfine grades. The reason for higher oil pick-up for spongy grades over their respective atomised grades can be explained by examining the SEM micrographs of these particles. As can be seen from Figs. 3.11 - 3.16, the spongy grades have some internal pores, and these also allow for the absorption of contaminants. This is consistent with what is suggested in the literature - that particles with more porosity increase their specific surface area, and this improves the sorption (Chun and Park, 2001; Ebner *et al.*, 2001; Toyoda *et al.*, 2002; Ngomsik *et al.*, 2005; Wu and Xu, 2005; Wu and Qu, 2005). Therefore, the spongy grades are both adsorptive and absorptive, making their pick-up higher than that of the corresponding atomised grades.

3.2.2.2 Annealed and un-annealed grades

As seen in Section 3.2.2.1, contaminant pick-up is influenced by whether the particles are atomised or spongy as well as by variation in particle size distribution. Although in the above experiments, the effect of annealing is not considered to be of significance, it is possible that in some circumstances this might not be the case. This concern is prompted by an examination of the SEM micrographs Fig. 3.13 and Fig. 3.16 where the annealed and un-annealed particles are seen to have different surface textures. However, this difference appears to be less pronounced in the case of the spongy grades and has also been confirmed by the manufacturer (Eklund, *Personal communication*).

An investigation into the possible effect of annealing (surface texture) on efficacy of removal is therefore worthy of investigation. Due to the range of the selected iron powders available, there are only four grades that can be categorised as being annealed or un-annealed. These are all fine grades, namely atomised un-annealed (A100S), atomised annealed (ASC100.29), spongy un-annealed (C100.29) and spongy annealed (NC100.24). Therefore, comparisons can only be made for these.

(i) Spongy fine grades: NC100.24 (annealed) versus C100.29 (un-annealed)

The results comparing the removal between the annealed spongy fine grade, NC100.24, and the un-annealed atomised fine grade, C100.29, is presented in Fig. 3.21. As can be seen there is little difference in the pick-up, within experimental error, for the annealed spongy fine grade, NC100.24, and the un-annealed spongy fine grade, C100.29. Specifically, the initial removal of the C100.29 is 40.53% and the respective figure of the NC100.24 is 39.84%. The maximum pick-up of the C100.29 is 99.75%, comparable to the 99.47% of the NC100.24. This is related to the difference in surface texture between C100.29 and NC100.24, not being very pronounced as can be seen from their SEM micrographs, Fig. 3.14 and Fig. 3.16, respectively.

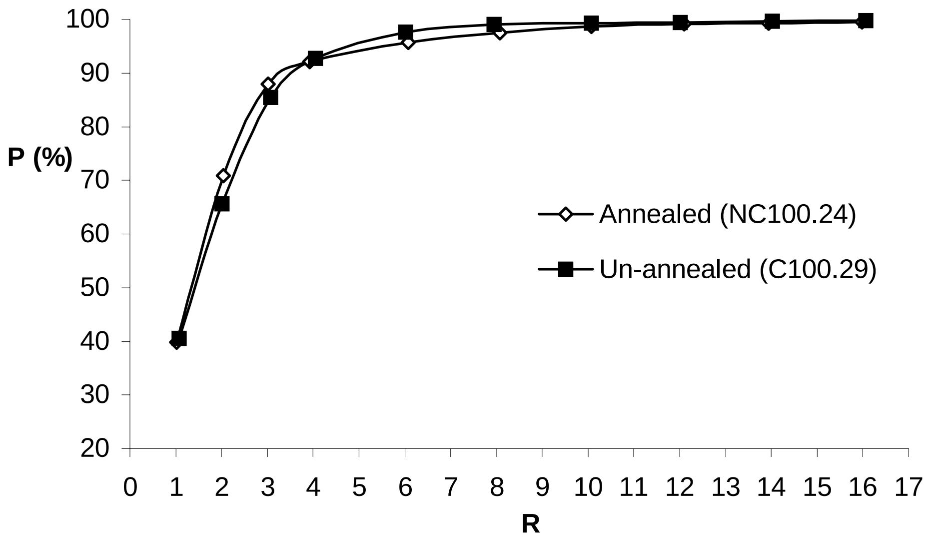

Figure 3.21: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, between annealed and un-annealed grades (*both spongy and fine*). Error bars (SE) have been omitted for clarity. The data are presented in Table 16 in Appendix 3.1.

(ii) Atomised fine grades: ASC100.29 (annealed) versus A100S (un-annealed)

The results comparing the removal between the annealed atomised fine grade, ASC100.29, and the un-annealed atomised fine grade, A100S, is presented in Fig. 3.22.

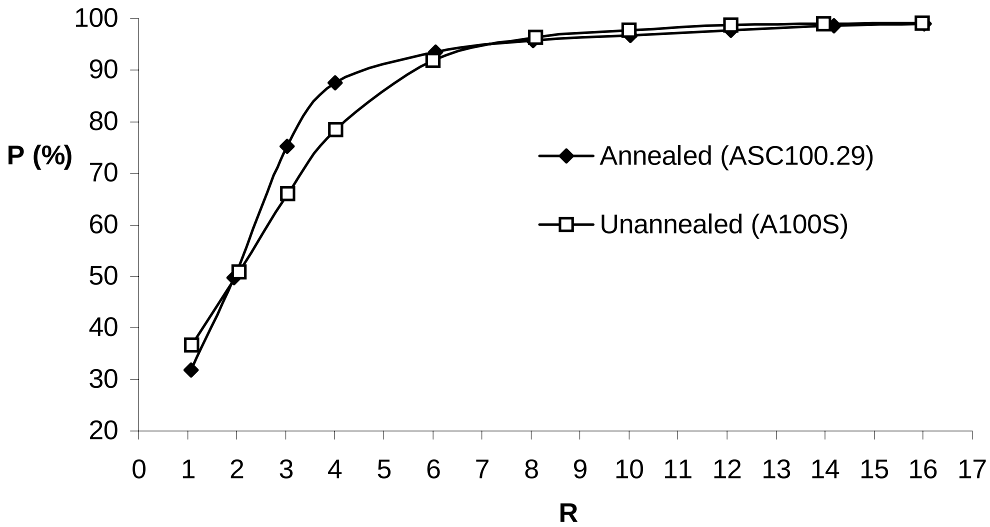

Figure 3.22: Comparison of the oil pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, between annealed and un-annealed grade (*both atomised and fine*). Error bars (SE) have been omitted for clarity. The data are presented in Table 17 in Appendix 3.1.

Unlike the case of the spongy grades, it is clearly seen from Fig. 3.22 that there is some difference in pick-up, especially for the initial removal, between the annealed atomised grade, ASC100.29, and the un-annealed atomised grade, A100S. Specifically, the initial pick-up of the A100S is 36.72%, significantly higher than 31.81% of the ASC100.29. The maximum pick-ups are different, showing 99.09% and 98.96% for the A100S and ASC100.29, respectively. Their SEM micrographs are shown in Fig. 3.13 and Fig. 3.15, respectively. It may be observed from these SEM micrographs that there is a noticeable difference in surface texture between them with the ASC100.29 grade being more nodular in surface texture.

It can therefore be seen that surface texture can make some difference with respect to removal efficacy, at least for atomised fine grades, although the effect is quite small and is not as pronounced as that of particle structure (resulting in the difference in the oil removal between spongy and atomised grades).

3.3 Characterisation of oil removal from a feather substrate

The methodology described in Section 2.1.1.2 for the removal of contaminants from feather clusters was employed. Unlike removal from a glass matrix, where the oil pick-up, P (%), is plotted against the particle-to-oil ratio, R, for feathers the oil removal, F(%), is plotted against the number of treatments, N. In general, it is found that for most grades and for most contaminants, the maximum removal can be achieved after 9 treatments (Ngeh, 2002). As with the previous studies on removal from a glass surface, the effect of particle size, particle shape and surface texture has been investigated.

3.3.1 The effect of particle size distribution

3.3.1.1 Atomised grades

Four atomised grades of iron particles were tested with regard to the pick-up of oil from feathers. The grades, in decreasing order of particle size are: coarse atomised un-annealed (A40S), fine atomised annealed (ASC100.29), fine atomised un-annealed (A100S) and superfine atomised annealed (ASC300). The average particle size for each of these grades is presented in Table 3.1, and ranges from 36 – 274 μm. The results of the oil pick-up for the atomised iron powder grades are shown in Fig. 3.23.

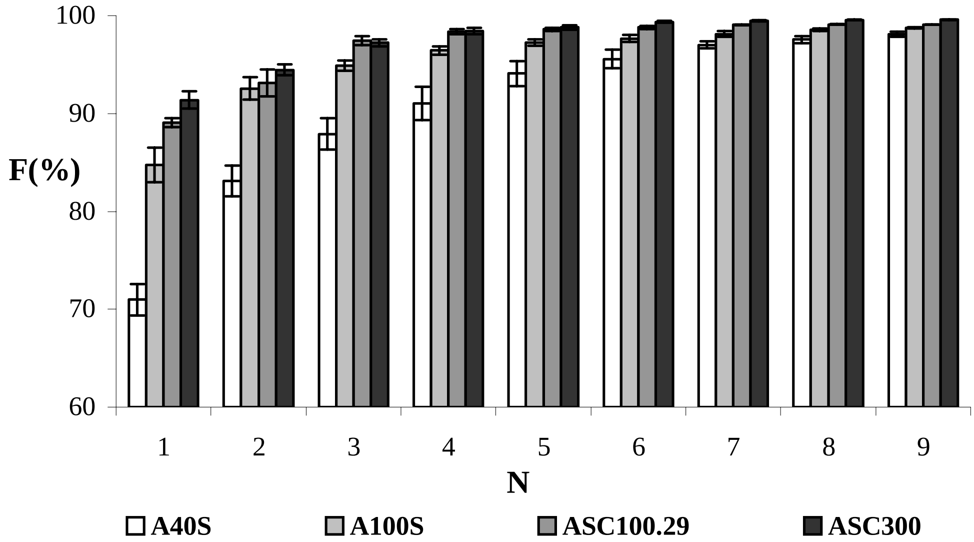

Figure 3.23: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, amongst different atomised grades of iron powder. Error bars represent the SE for five replicates. The data are presented in Table 9 in Appendix 3.2.

The results show that the oil pick-up increases as the particle size decreases and this dependency is more pronounced for the earlier treatments. Specifically, the initial pick-up is very different amongst the grades. For instance, the coarse grade, A40S, shows a removal of 70.97% that is considerably lower than the corresponding removals of 84.72% and 89.07% of the fine grades, A100S and ASC100.29, respectively. These removals are, in turn, lower than the 91.37% for the superfine grade, ASC300. However, the maximum oil removal, after 9 treatments, is more comparable between the grades. Thus the coarse grade, A40S, shows a removal of 98.11% that is lower than the corresponding removals of 98.76% and 99.09% of the fine grades, A100S and ASC100.29, respectively. These removals are, in turn, lower (at the SE level) than the 99.59% for the superfine grade, ASC300. Overall, it can be concluded that the superfine grade is superior.

3.3.1.2 Spongy grades

Similarly, four spongy grades were tested with regard to the pick-up of oil from feathers. The grades, in decreasing order of particle size are: coarse spongy un-annealed (M40S), fine spongy annealed (NC100.24), fine spongy un-annealed (C100.29) and superfine spongy annealed (MH300.29). The average particle size for each of these grades is shown in Table 3.2, and ranges from 37 - 185 μm. The results of the oil pick-up for the spongy iron powder grades are shown in Fig. 3.24.

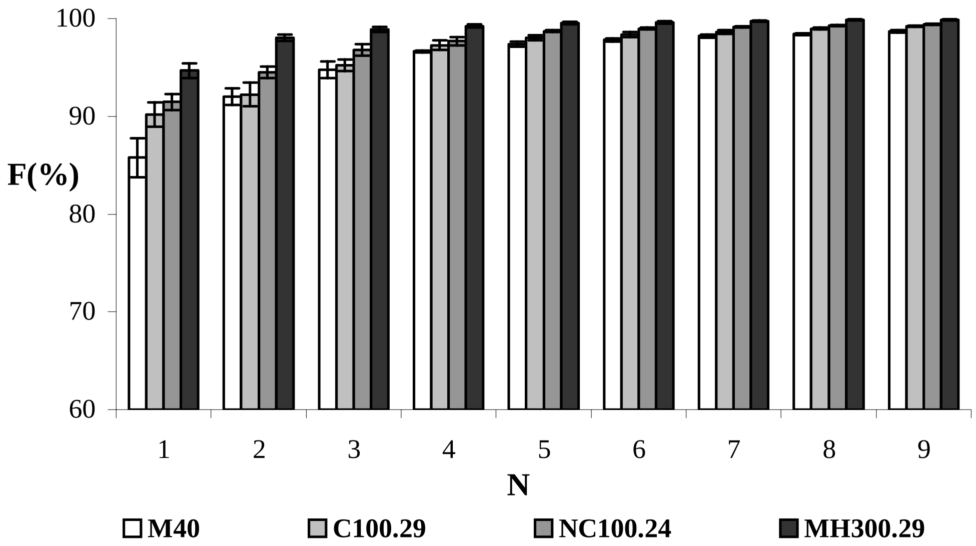

Figure 3.24: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, amongst different spongy grades of iron powder. Error bars represent the SE for five replicates. The data are presented in Table 10 in Appendix 3.2.

As expected, the oil pick-up increases as the particle size decreases and, as for the atomised grades, this dependency is more pronounced for the earlier treatments. Specifically, the superfine grade, MH300.29, shows the highest oil removal overall, followed by the fine grades NC100.24 and C100.29. The coarse grade M40, with the largest particle size of all the spongy grades tested, has the lowest overall oil removal. Regarding the initial removal, the 85.76% achieved by M40 is significantly lower than the corresponding figures of 90.20% and 91.47% for the fine grades, C100.29 and NC100.24, respectively. These removals are, in turn, lower than the 94.68% achieved by the superfine grade, MH300.29. With regard to the maximum removal, the superfine MH300.29 is the most impressive, achieving up to 99.88% removal that is higher (at the SE level) than the corresponding removals of 99.21% and 99.42% of the two fine grades, C100.29 and NC100.24, respectively. The coarse grade, M40, is less impressive, achieving a maximum removal of 98.70% that is lower than the above. Hence, the removal efficacy increases in the order: coarse, fine to superfine. In general, for the fine and superfine grades, a removal in excess of 99.2% is achieved and, again, the superfine can be concluded to be superior.

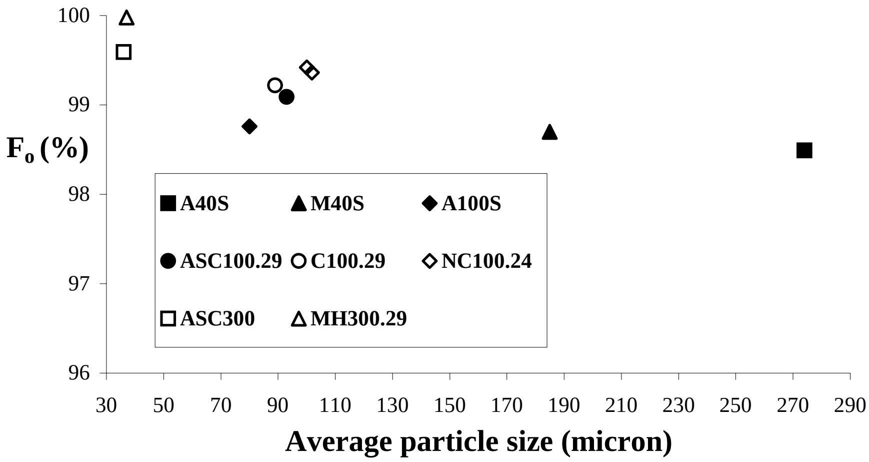

Figure 3.25: A plot of the maximum removal, F_o (%), from feathers versus the estimated average particle size for the different grades of iron powder. The data are presented in Table 11 in Appendix 3.2.

Yet again, it has been demonstrated that for both inorganic (glass surface) and organic (feathers) matrices, surface texture, particle shape and particle size have important roles to play in determining the efficacy of contaminant removal. Not unexpectedly, the superfine grade is the most effective. This is related to a greater contact surface area for a given weight (Chun and Park, 2001; Ebner *et al.*, 2001; Oliveira *et al.*, 2002; Ngomsik *et al.*, 2005; Yean *et al.*, 2005; Wu and Xu, 2005; Wu and Qu, 2005). The effect of the particle size distribution on the maximum contaminant removal, F_o(%), from feathers is illustrated in Fig. 3.25.

3.3.2 The effect of particle shape (structure) and surface texture

3.3.2.1 Atomised and spongy grades

(i) Coarse, un-annealed grades: A40S (atomised) versus M40 (spongy)

Two of the particle types, A40S and M40 (Fig. 3.9 and Fig. 3.10 respectively) are in the "coarse, un-annealed" category. They may be considered to differ in shape (or structure) only. Thus the difference between the atomised A40S and the spongy M40 is that the latter is more granular, with a greater potential for various enclosures on the surface. Fig. 3.26 compares the efficacy of oil removal from feathers for these two grades.

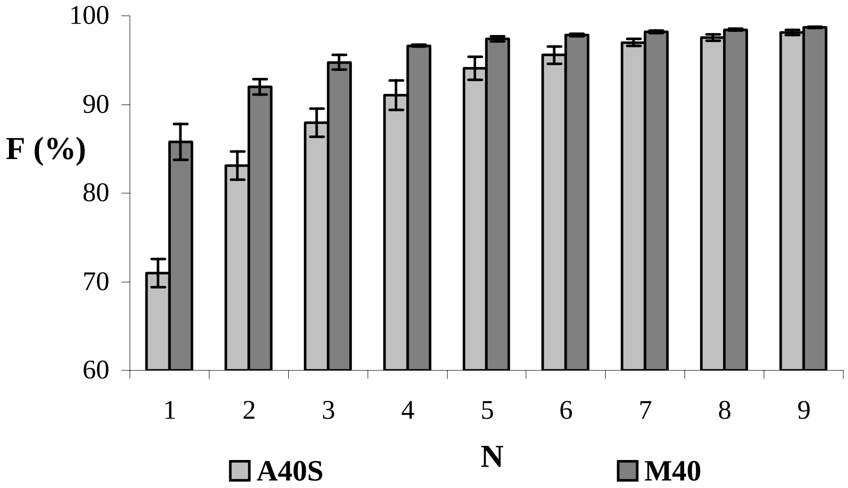

Figure 3.26: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, between atomised and spongy grades of iron powder (*both coarse and un-annealed*). Error bars represent the SE for five replicates. The data are presented in Table 12 in Appendix 3.2.

It can be seen from Fig. 3.26 that the removal is lower for the coarse atomised un-annealed grade, A40S, than for the spongy coarse un-annealed grade, M40. Specifically, the initial pick-up of 70.97% for A40S is significantly lower than that of 85.76% for M40. The maximum removal of A40S, after nine treatments, is 98.11%, considerably lower (at the SE level) than 98.70% of M40. The SEM photographs of A40S and M40 grades are shown in Fig. 3.9 and Fig. 3.10, respectively.

(ii) Fine, un-annealed grades: A100S (atomised) versus C100.29 (spongy)

For the fine un-annealed grades, it can be seen from Fig. 3.27 that the removal is lower for the atomised fine un-annealed grade, A100S, than for the spongy fine un-annealed grade, C100.29. The initial pick-up for A100S is 84.72%, considerably lower than 90.20% for C100.29. The maximum removal, after 9 treatments, is 98.76% for A100S, significantly lower (at the 95% interval confidence level) than 99.21% for C100.29. It should be noted that the estimated average particle sizes for these grades are comparable at 80 and 93 μm for A100S and C100.29 respectively. The SEM photographs of A100S and C100.29 are shown in Fig. 3.13 and Fig. 3.14, respectively.

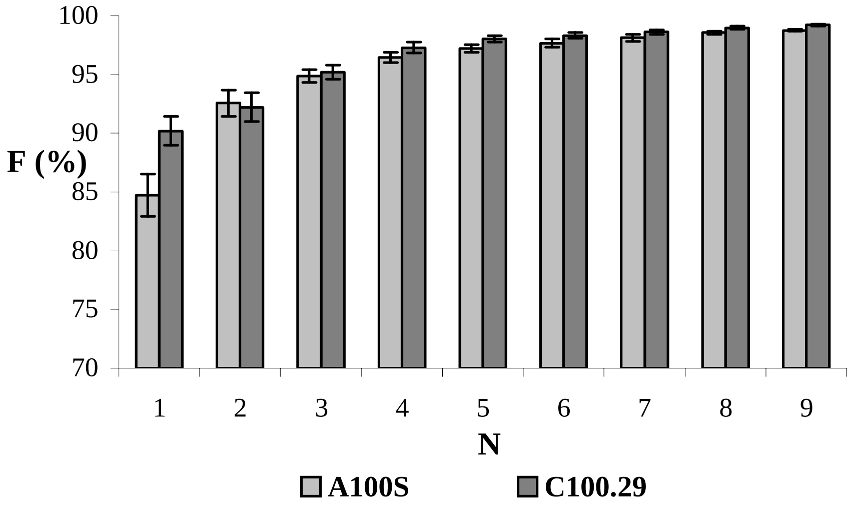

Figure 3.27: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, between atomised and spongy grades of iron powder (*both fine and un-annealed*). Error bars represent the SE for five replicates. The data are presented in Table 13 in Appendix 3.2.

(iii) Fine, annealed grades: ASC100.29 (atomised) versus NC100.24 (spongy)

The comparison of oil removal from feathers between the atomised fine annealed grade, ASC100.29, and the spongy fine annealed grade, NC100.24, is shown in Fig. 3.28.

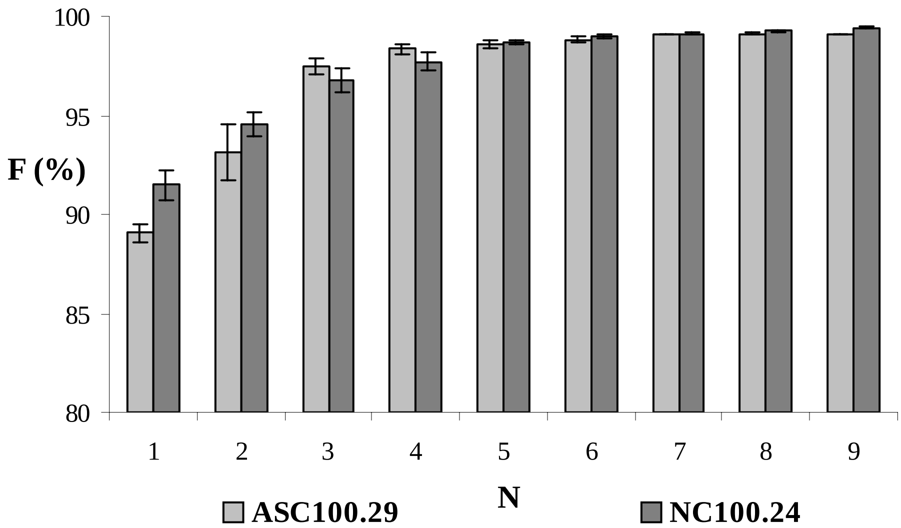

Figure 3.28: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, between atomised and spongy grades of iron powder (*both fine and annealed*). Error bars represent the SE for five replicates. The data are presented in Table 14 in Appendix 3.2.

As can be seen the removal is lower for ASC100.29 grade than for NC100.24 grade. For initial removal, it is 89.07% for ASC100.29, which is considerably lower than 91.47% for NC100.24. The maximum removal, after 9 treatments, is 99.09% for ASC100.29, significantly lower (at the 95% interval confidence level) than 99.42% for NC100.24. Their SEM photographs are shown in Fig. 3.15 and Fig. 3.16, respectively.

(iv) Superfine, annealed grades: ASC300 (atomised) versus MH300.29 (spongy)

For the superfine annealed grades, it can be seen from Fig. 3.29 that the removal is lower for the atomised superfine annealed grade, ASC300, than for the spongy superfine annealed grade, MH.300.29. The initial removal of ASC300 is 91.37%, which is considerably lower than 94.68% achieved by MH300.29. The maximum removal is significantly different (at the SE level), where 99.59% and 99.88% is achieved for ASC300 and MH300.29, respectively, Fig. 3.29. The respective SEM photographs of the ASC300 and MH300.29 are shown in Fig. 3.11 and Fig. 3.12.

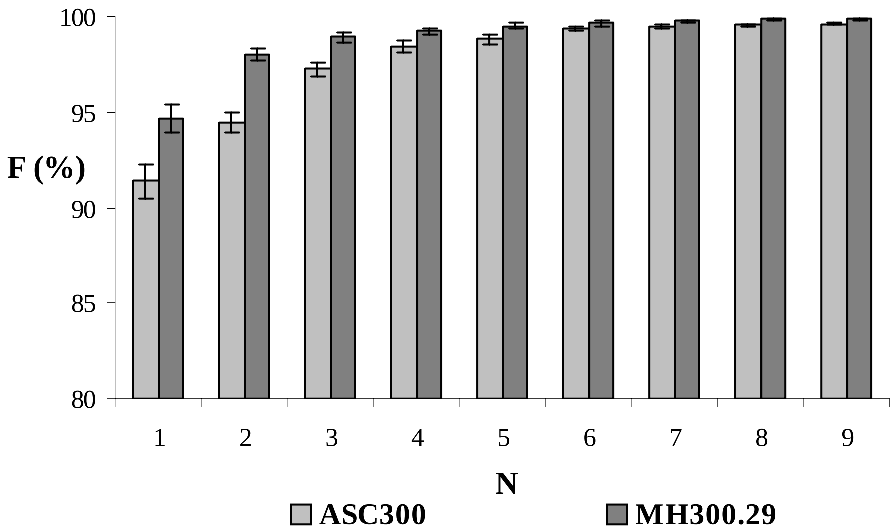

Figure 3.29: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, between atomised and spongy grades of iron powder (*both superfine and annealed*). Error bars represent the SE for five replicates. The data are presented in Table 15 in Appendix 3.2.

From this study it would appear that the additional structural feature of the spongy grade, namely porosity (or "*sponginess*") has a significant advantage in the pick-up. This is explained in Section 3.2.2.1. Thus, the oil pick-up is lower for the atomised iron powder than for the spongy iron powder. The difference in the oil removal between the atomised and spongy grade becomes less pronounced as the number of treatments increases. Again, the difference in the oil removal between the atomised and spongy is more pronounced for coarse grades than for fine and superfine grades. The spongy grades approach their maximum oil removal value more quickly than the respective atomised.

3.3.2.2 Annealed and un-annealed grades

As with the experiments on oil removal from a petri dish, *vide supra,* experiments on the effect of iron particle surface texture (annealed vs. un-annealed) on oil removal from feathers have also been conducted. Four fine grades categorised as either annealed or un-annealed were used. These are fine atomised un-annealed (A100S), fine atomised annealed (ASC100.29), fine spongy un-annealed (C100.29) and fine spongy annealed (NC100.24).

(i) Spongy fine grades: NC100.24 (annealed) versus C100.29 (un-annealed)

The comparison of oil removal from feathers between the annealed spongy fine grade, NC100.24, and the un-annealed spongy fine grade, C100.29, is shown in Fig. 3.30.

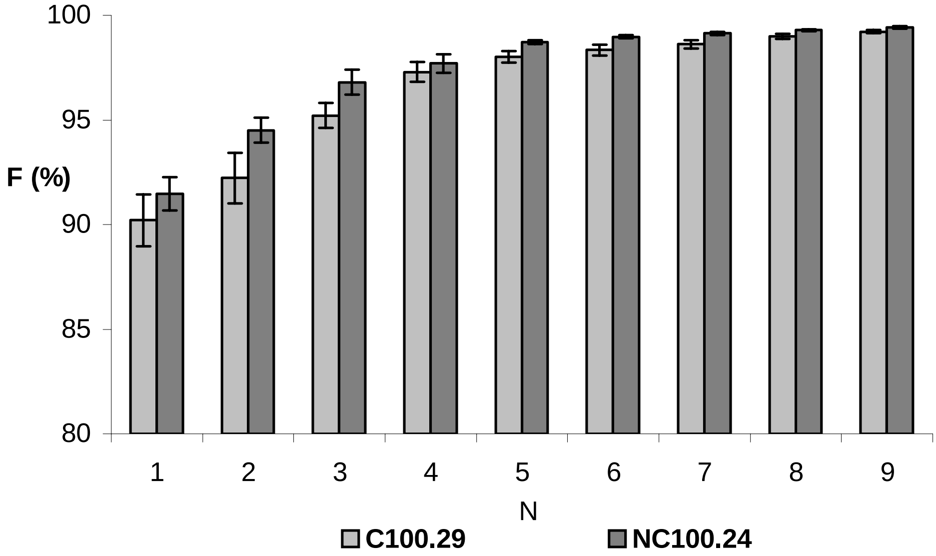

Figure 3.30: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, between annealed and un-annealed grades of iron powder (*both spongy and fine*). Error bars represent the SE for five replicates. The data are presented in Table 16 in Appendix 3.2.

It can be seen from Fig. 3.30 that NC100.24 tends to demonstrate a higher removal than C100.29. Specifically, the initial removal of NC100.24 is 91.46%, compared to 90.20% of C100.29. The maximum removal, after 9 treatments, of NC100.24 is 99.42%, higher (at the SE level) than 99.22% of C100.29. The SEM photographs of these materials are shown in Fig. 3.14 and Fig. 3.16, respectively.

(ii) Atomised fine grades: ASC100.29 (annealed) versus A100S (un-annealed)

It appears from Fig. 3.31 that there is a difference in the removal, especially for the initial removal, between the annealed atomised fine grade, ASC100.29, and the un-annealed atomised fine grade, A100S. The initial pick-up of ASC100.29 is 89.07%, higher than 84.72% of A100S. Regarding the maximum removal, this figure is 99.09% for ASC100.29, higher (at the SE level) than 98.76% for A100S. Overall, in can be seen that the annealed grade, ASC100.29, is superior. The SEM photographs of these materials are shown in Fig. 3.13 and Fig. 3.15, respectively. It may be observed from these SEM micrographs that there is a noticeable difference in surface texture between the two materials with the ASC100.29 grade being more nodular in surface texture than the A100S grade. This facilitates the sorption, resulting in the higher oil removal for the ASC100.29 over the other grade. This is consistent with a previous study, which suggests that an increase in roughness of the surface texture of sorbents will enhance sorption by physical trapping (Radetic *et al*., 2003).

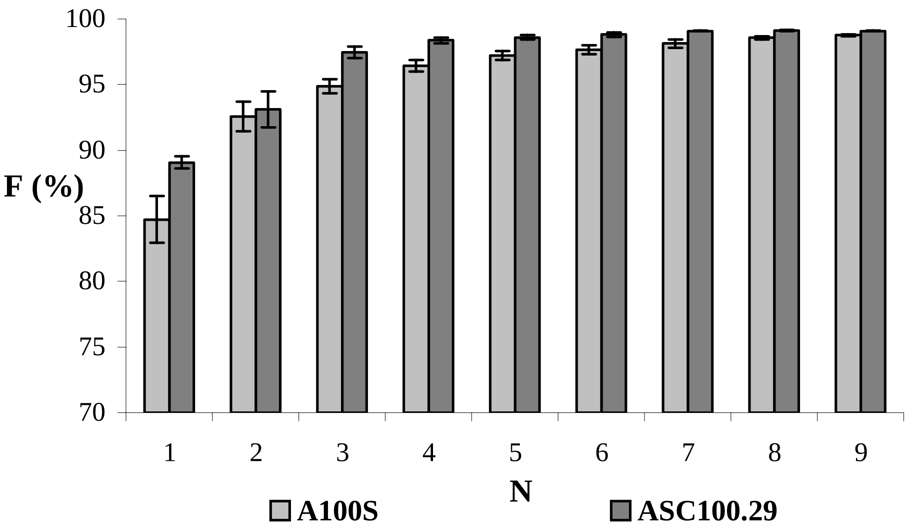

Figure 3.31: Comparison of the oil removal, F (%), from feathers as a function of the number of treatments, N, between annealed and un-annealed grades of iron powder (*both atomised and fine*). Error bars represent the SE for five replicates. The data are presented in Table 17 in Appendix 3.2.

It can be observed from Figs. 3.30 to 3.31 that, for contaminant removal from feathers the annealed iron powder has higher pick-up than the un-annealed iron powder. Interestingly, this is in contrast to the oil pick-up from a petri dish in which the un-annealed is found to be slightly better than the annealed. This is probably related to the nature of matrix that is very different between glass and feathers. It is also worth noting that the improvement in removal for the annealed compared to the un-annealed is more pronounced for the atomised than for the spongy. This is probably due to the difference in surface texture between annealed and un-annealed is more pronounced for the atomised grade than for the spongy grade, see Figs. 3.13 to 3.16, as previously explained.

3.4 Identifying an optimal grade of magnetic particle for oil removal

For the eight different grades of iron powder tested, the “optimal” grade is considered to be that which ultimately achieves maximum contaminant removal, preferably approaching 100%. Therefore, comparisons of oil removal from both glass and feathers were made for different grades of iron powder, and the results are presented in Figs. 3.32 - 3.33.

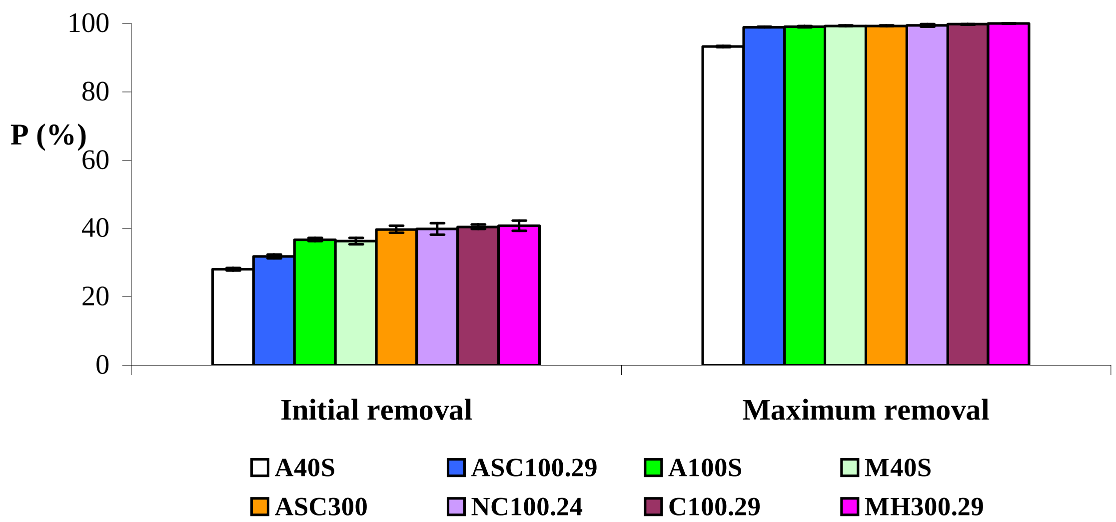

Figure 3.32: The initial and maximum oil pick-up from a petri dish for different grades of iron powder. Error bars represent the SE for five replicates. The data are presented in Table 18 in Appendix 3.2.

As can be seen from Fig. 3.32, an initial pick-up exceeding 36% is achieved for all grades excluding A40S. The superfine spongy annealed grade, MH300.29 has the highest pick-up, showing up to 40.84%. Regarding the maximum removal, P_o (%), a removal exceeding 99.3% is achieved for all the spongy grades, of which the superfine spongy annealed grade, MH300.29, removes up to 99.99%.

Fig. 3.33 shows that there is considerable variation between the different grades with respect to their initial removal, particularly between A40S (atomised coarse grade) ca. 71%, and MH300.29 (spongy superfine grade), ca. 95%. Such variation becomes less pronounced as the number of treatments increases. Thus for the final removal, A40S shows a removal of ca. 98% and MH300.29 shows a removal of ca. 100%.

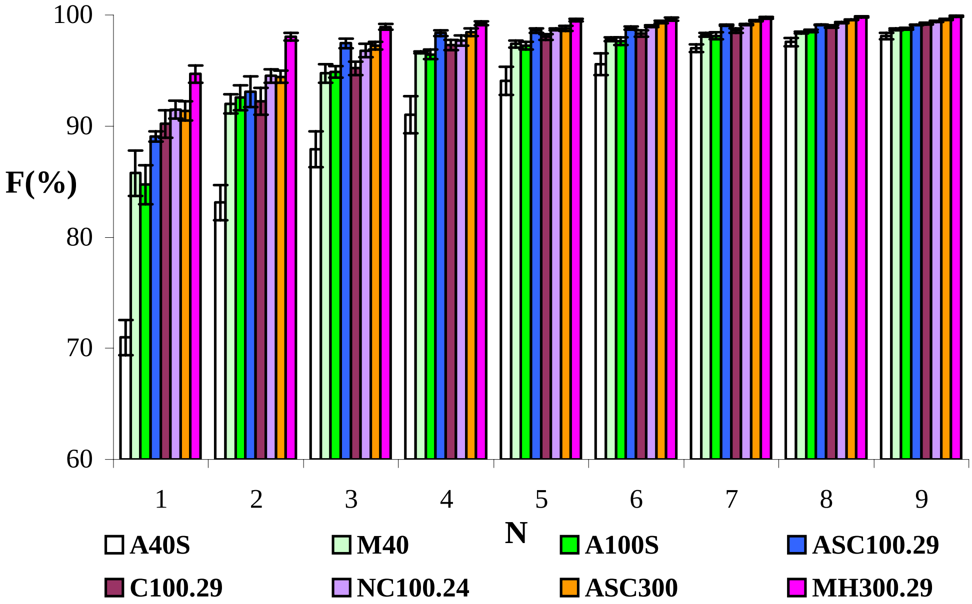

Figure 3.33: Histogram of the oil removal, F (%), from feathers as a function of the number of treatments, N, for 8 different grades of iron powder. Error bars represent the SE for five replicates. The data are presented in Table 19 in Appendix 3.2.

From these investigations, it can be seen that the superfine spongy annealed grade of iron powder, MH300.29, is the most efficient for both glass and feathers. Therefore, this grade is optimal for both of these substrates.

The finding that the MH300.29 grade is the most effective validates the preceding experiments that were designed to elucidate the various physical attributes that contribute to improved efficacy, namely, the superiority, with respect to oil removal (from both a glass matrix and feather substrate), of spongy grades over atomised grades and of superfine grades over fine and coarse grades. It is also noted that the effect of annealing (surface texture) on oil removal is not as pronounced as the effects of other physical properties such as particle size and particle shape. Therefore, the grade that is consistent with these requirements, MH300.29, characterised as superfine and spongy, is expected to “win out”. By looking at the SEM photograph of the MH300.29, Fig. 3.12, it can be seen that this grade is not only very fine but also has pores inside the individual particles and these properties facilitate the sorption of oil, resulting in the highest removal of all the grades tested.

Having identified an “optimal grade” of iron powder for the removal of the representative oil, subsequent experiments were designed to assess the efficacy of removal for a further six contaminants, ranging from a light crude to a highly viscous oil and including two oil/seawater emulsions. The MH300-29 grade will be referred to as the “optimal grade” in subsequent chapters.

3.5 Conclusions

The effects of different physical characteristics amongst different grades of iron powder (such as particle size, shape (structure) and surface texture) on the pick-up of a “representative” oil from both a petri dish and from feathers have been investigated. Eight different grades of iron powder have been investigated.

With respect to particle size, it was found (not unexpectedly) that the finer the grade, the higher the pick-up - for both the glass substrate and for feathers. It was also found that, for removal from feathers, that differences are more pronounced for the earlier treatments.

With respect to particle shape or “structure”, a comparison between “spongy” and “atomised” grades across all particle sizes (coarse, fine and superfine) demonstrated that the spongy grades have higher removal than the atomised grades. It was noted, however, that the differences are more pronounced as the particle size of the grade increases for oil removal from both glass and feathers. Also, for oil removal from feathers, differences become less pronounced as the number of treatments increases.

With respect to surface texture, a comparison between annealed and un-annealed grades on oil removal from glass and feathers demonstrated that, for comparable particle size and shape, the annealed is slightly more efficient in the removal from feathers but the reverse is found to be true for removal from glass. This is probably related to the increased surface roughness of annealed particles compared to un-annealed particles, *vide supra.*

Overall, in light of the above, the superfine spongy annealed grade, MH300.29, is identified as being the most effective showing ca. 100% oil removal (within experimental error) from both glass and feathers. This particular grade was employed in all subsequent experiments and will henceforth be referred to as the “optimal grade”.

3.6 References

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CHAPTER 4: APPLICATION OF THE OPTIMAL GRADE OF MAGNETIC PARTICLES TO THE REMOVAL OF *FRESH* OIL AND EMULSION FROM GLASS AND FEATHERS

4.5.1 Preliminary tests on removal of fresh oil from plumage

4.5.2 Challenges relating to experiments on whole bird models

4.5.3 Removal of fresh oil from plumage

4.6 Comparison of removal between feather clusters and plumage

4.7 Comparison of maximum removal between glass and feathers

4.8 Comparing removal efficiency for different contaminants using an empirical model

4.9 Comparing removal efficiency for different substrates (matrices) using an empirical model

4.10 Conclusions

4.11 References

CHAPTER 4: APPLICATION OF THE OPTIMAL GRADE OF MAGNETIC PARTICLES TO THE REMOVAL OF *FRESH* OIL AND EMULSION FROM GLASS AND FEATHERS

4.1 Introduction

When an oil spill occurs, wildlife and birds can be affected. Thanks to the development of modern communication technology, news on spills spreads quickly worldwide (IPIECA, 2004). Rescue operations are usually implemented shortly afterwards, such as in the case of the MTV Treasure oil spill (IBRRC, 2005). In such situations, most of the affected animals can be found and collected without significant delay and the oiling can often be considered to be quite “fresh”. Emulsification of oil can also occur being one of the phases in the weathering process of oil (ITOPF, 2004). When oil is emulsified, it increases in viscosity and volume, and forms a “mousse-like” substance that is also more persistent in the environment (ITOPF, 2004) hence making response techniques more difficult (IPIECA, 2001; NOAA, 2004). As with oil itself, emulsion has adverse effects on wildlife in general, and on birds in particular (Piatt *et al.*, 1990; Dicks, 2004). In this regard, studies have been reported on the removal of both fresh oil and emulsion from feathers (Bassères *et al.*, 1994).

Having identified an optimal grade of iron powder, namely “spongy superfine annealed”, MH300.29, with respect to the removal of a representative oil (Arab medium crude oil) from a glass surface (petri dish) and feather clusters, this grade was then tested in the same way with respect to other fresh oils and emulsions. It is assumed that the optimum characteristics of MH300.29 will be generally manifested. The experiments described herein test (and bear out) this assumption. The oils tested include Merinie crude oil (MO), Gippsland crude oil (GO), Arab medium crude oil (AO), engine oil (EO) and bunker oil 1 (BO1). These oils, as presented in Table 2.2, are different in viscosity and categorised, in turn, as light (MO, GO), medium (AO) and heavy (EO and BO1). The two emulsions tested are: emulsion1 (Gippsland oil/seawater) (ES1), and emulsion2 (engine oil/seawater) (ES2). The method for making these emulsions is adapted from Bassères *et al.* (1994) and briefly presented in Section 2.2.1.2, Chapter 2. The experiments were carried out on petri dish, duck and penguin feather clusters and penguin feather plumage. All experiments were conducted in five-fold replicate and at a room temperature of ca. 293 K, unless otherwise stated.

4.2 Removal of fresh oil and emulsion from a glass surface

4.2.1 Experimental details

The method for determination of fresh oil pick-up from a petri dish using the optimal magnetic particle grade was similar to that mentioned in Section 2.1.1. Five different types of oils, *vide supra*, AO, MO, GO, EO and BO1 and two emulsions, namely ES1 and ES2 were used for the experiments.

4.2.2 Results and discussion

The results of these experiments are shown in Figs. 4.1 to 4.3.

4.2.2.1 Comparison amongst light, medium and heavy oil

It can be seen from Fig. 4.1 that the pick-up is, in general, lower for the light oils (GO and MO) than for the medium oil (AO) that is, in turn, lower than for the heavy oils (EO and BO1). The increase in oil pick-up as the viscosity of the oil increases has been observed in other oil-sequestration studies, *albeit* utilizing different sorbent materials and substrates (Radetic *et al.*, 2003, Duong and Burford, 2006). Specifically, the initial removal (at R = 1) is significantly lower for the lighter oils than for the heavier ones. Thus, for R = 1, no removal greater than 50% is achieved for the light oils whereas for EO and BO1 pick-ups of 59.2% and 81.8%, respectively are obtained. Although the difference in the maximum pick-up (R > 12) is not very pronounced between light and heavy oils, a higher removal of the heavy oils compared to the light ones is still evident. It was also noted that the R_o needed to achieve the maximum pick-up is higher for light oils than for heavy oils (18 compared to 12). In particular, for the lightest oil tested, GO, the maximum removal of 98.33% is obtained at $R_o = 18$, while the respective figure for the most viscous oil, EO, is 99.68% at $R_o = 12$, Fig. 4.1. These values are significantly different at the 95% level. In this regard, during the experiments on GO, it was observed that an oil residue remains on the petri dish after each treatment. This results in an overall lower efficacy, even though the tests are conducted up to $R_o = 18$. This is an interesting observation that raises the possibility of an oil component that adheres very strongly to the glass surface. No attempt has been made at this stage to identify this component since this is outside of the scope of this thesis. Notably, as will be discussed in a subsequent section, this does not present a problem with respect to the removal of oil from feathers.

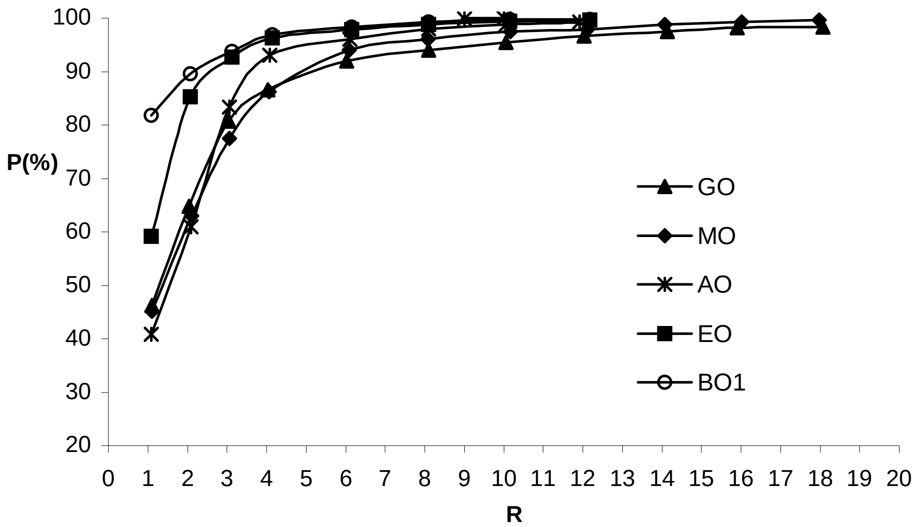


Figure 4.1: Comparison amongst light, medium and heavy oil for the pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R. Error bars are omitted for clarity. The data are presented in Table 1 in Appendix 4.1.

4.2.2.2 Comparison between oil and emulsion

The comparison of oil removal from a petri dish between oils and their respective emulsions is shown in Fig. 4.2.

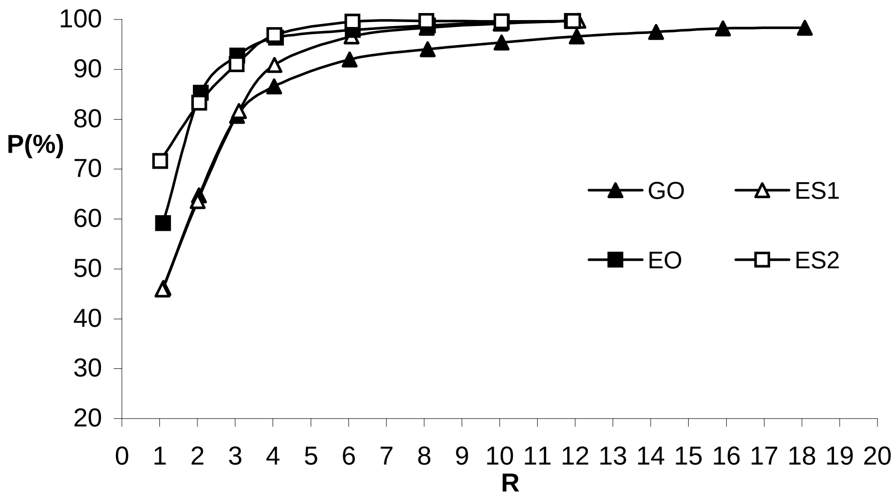


Figure 4.2: Comparison between oils and their respective emulsions for the pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R. Error bars were omitted for clarity. The data are presented in Table 2 in Appendix 4.1.

Interestingly, the pick-up for two selected oil/sea water emulsions is higher than for the respective oils themselves, Fig 4.2. Specifically, the initial pick-up is 59.18% for EO, significantly lower than the 71.60% for ES2, whilst the initial removal is almost identical for both light oil and emulsion at 46.2% and 45.9% for GO and ES1, respectively. With respect to the maximum removal, GO reaches a plateau at 98.33%, lower than 99.74% for ES1. This is in contrast to the experiments on feathers that show a higher removal for the oils than for their emulsions. This is further discussed in Section 4.4.

4.2.2.3 Comparison amongst all contaminants

The comparison of the initial and maximum removals from a petri dish for all contaminants is depicted in Fig. 4.3.

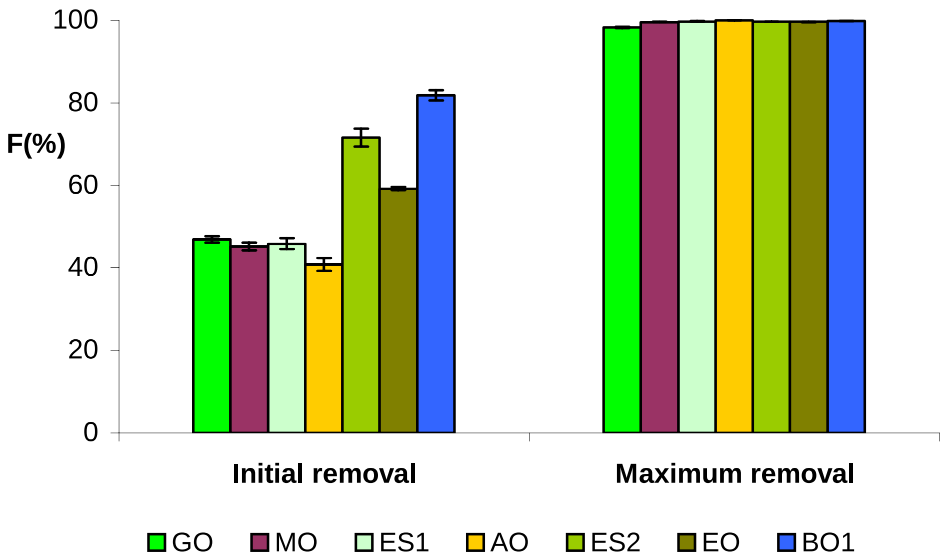


Figure 4.3: Comparison of the initial and maximum pick-up, P (%), from a petri dish as a function of the particle-to-oil ratio, R, for all contaminants. Error bars represent the SE for five replicates. The data are presented in Table 3 in Appendix 4.1.

Fig. 4.3 shows that the initial pick-up is significantly different amongst the contaminants, ranging from 40.84% for AO to 81.83% for BO1. However, the maximum pick-up is much more comparable, showing ca. 100% for most of the contaminants tested with the exception of GO.

4.3 Blank test on feather clusters

It is a habitual practice of birds to preen their feathers. In doing so, the feathers are oiled with a substance secreted by the preen gland, also known as the uropygial gland, near the tail (Gill, 1990). It has been suggested that preening oil provides a protective role when applied to the feathers (Jacob and Ziswiler, 1982). Some of the components of preening oils are considered to provide protection from plumage-degrading organisms such as bacteria and fungi (Jacob *et al.*, 1982; Moyer *et al.*, 2003). However, the role of preening oil in contributing to the waterproofing of feathers is still surrounded by controversy in the literature (Montalti and Salibian, 2000; Sweeney *et al.*, 2004). Some authors suggest that preening oil is not directly responsible for waterproofing but contributes by helping to keep the feathers supple and aligned (Rijke, 1970; Moyer *et al.*, 2003), hence maintaining a waterproofing microstructure and this is often referred to as the "textile model" (Cassie and Baxter, 1944; Croxall, 1972). Smail (1978) and Kerley and Erasmus (1987) have even argued that feather microstructure (when in good condition is, in itself, sufficient to repel water) whereas the preening oil is merely responsible for helping to maintain the microstructure. However, other researchers suggest that preening oil has a more important role in water repellence (Jacob and Ziswiler, 1982). Other possible functions of preening oil can be found in Montalti and Salibian (2000) and Sweeney *et al.* (2004).

Irrespective of the detailed role(s) of preening oil(s), it is obviously desirable for these to be either retained or regenerated as soon as possible after treatment. Conventional methods of treatment, in particular detergent-based methods, are known to result in the removal of preening oil(s) (Jenssen, 1994). For magnetic cleansing, it is not clear to what extent preening oil(s) are removed, although it has been shown that the feather microstructure is essentially restored to its original condition by this method, suggesting that the microstructure remains supine. A detailed investigation in this regard would involve the application of a technique such as gas chromatographic analysis, due to the very small quantities of preening oil expected to be present on the feathers – this is not within the scope of this thesis. However, to be scientifically rigorous, blank gravimetric experiments have been conducted to assess whether magnetic particles can affect a significant change in the mass of virgin feather clusters.

The experimental details are as follows. A pre-weighed feather cluster (m_1) was immersed and agitated with an excess of the optimal grade of iron powder. The magnetic particles were then harvested using a magnetic tester. The "stripped" feather cluster was then re-weighed (m_2). The ratio, B, of the weight of the feather before and after treatment, was calculated using Equation 4.1

$$B\ \% = (m_1 / m_2) \times 100\% \qquad (4.1)$$

This was performed in five-fold replicate and the results are shown in Fig. 4.4.

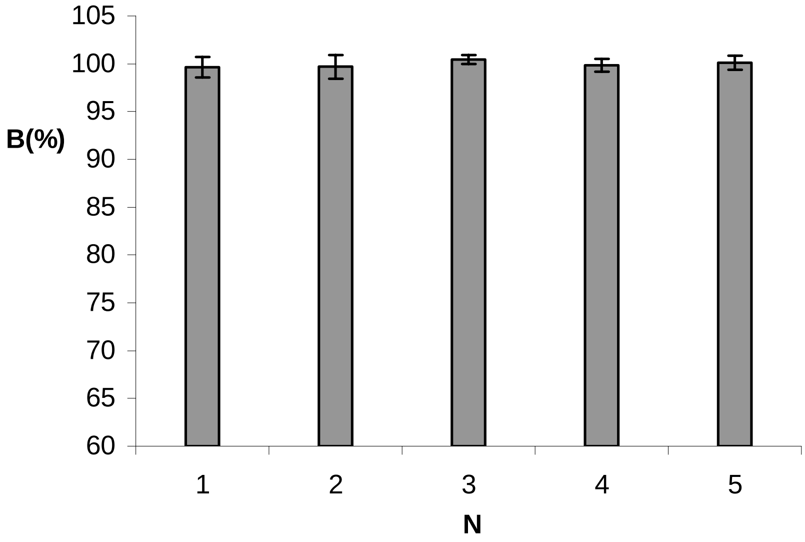


Figure 4.4: Blank test on duck feathers using the magnetic particles. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 4 in Appendix 4.1.

The results from the blank tests, Fig. 4.4, show that there is no significant difference in the weight of the cluster before and after treatment with magnetic particles. Therefore, it is not considered necessary to make systematic blank corrections for the experiments that are conducted in the present work. However, the current method does not enable to be answered the question of whether preening oil(s) are actually removed by magnetic cleansing.

4.4 Removal of fresh oil and emulsion from feather clusters

4.4.1 Experimental details

The methodology for the determination of the amount of fresh oil removed from feather clusters by the optimal magnetic particle grade of iron powder, was similar to that described in Section 2.2.2. Feathers were taken from the Mallard Duck (*Anas platyrhynchos)* and the Little Penguin (*Eudyptula minor*). The same oils as mentioned previously were used. Namely, the light oils, MO and GO, the medium oil - AO, and the heavy oils: EO and BO1. In addition, the experiments were also carried out for two emulsions: ES1 and ES2. For each contaminant up to nine treatments were conducted until the feather appear to be clean and, more importantly (quantitatively), a maximum removal is attained. The number of treatments up to the maximum removal is found to be different, depending on the contaminant tested. When fresh oil is involved, previous results have indicated that nine treatments are sufficient for maximum removal (Ngeh, 2002).

4.4.2 Duck feather clusters

The results of these experiments are shown in Figs. 4.5 to 4.7.

4.4.2.1 Comparison amongst light, medium and heavy oil

As can be seen from Fig. 4.5, for early treatments the removal increases with decreasing the viscosity of the oil. This is consistent with previous studies, using different sorbents and substrates, suggesting that the sorption of oil decreases as oil becomes heavier (Toyoda *et al.*, 2000; Saito *et al.*, 2003; Li *et al.*, 2004). In particular, the initial removal is significantly lower for heavier oils than for lighter oils. For example, initial removals are 60.94% and 73.51% for BO1 and EO, respectively. This is much lower than the 94.67% obtained for AO, which is lower again than the 97% minimum removal obtained for MO and GO. The initial removal is an important consideration in the light of applying such technology in the field since it relates to the amount of oil that can be quickly removed from an oiled bird upon first encounter. The rapid removal of a significant amount of contaminant would greatly reduce the risk of oil ingestion due to preening during transportation and assist in the initial stabilisation process (Clark *et al.,* 1997). It was also observed that the difference in oil removal between light oils and heavy oils becomes less pronounced as the number of treatments increases. Thus, the maximum pick-up, achieved after seven to nine treatments, is more comparable between different types of oil and, in fact, approaches 100% for all the oils tested. However, it is worth noting that the actual number of treatments needed to achieve maximum removal depends on the type of oil, being less for the lighter varieties (e.g. 7 treatments for GO compared to 9 treatments for EO). This suggests that the removal efficiency is higher for light oils than for heavy oils, even though their final removal efficacy is almost the same.

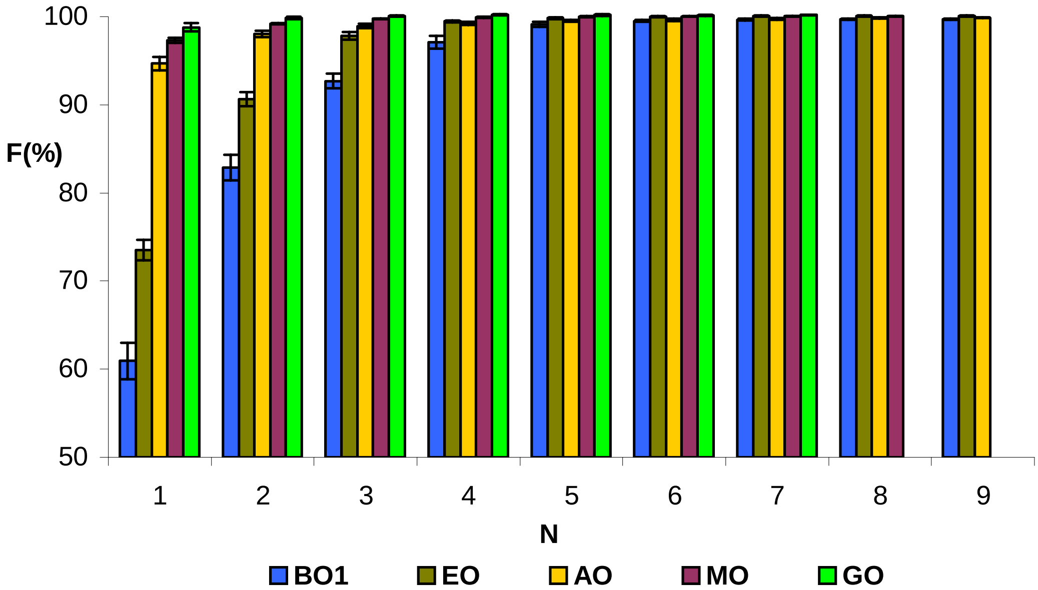


Figure 4.5: Comparison amongst light, medium and heavy oils for the pick-up, F (%), from duck feathers as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 12 in Appendix 4.1.

The finding that the initial removal decreases with increasing oil viscosity suggests that lighter fractions are more susceptible to removal. Therefore, it is not surprising that the oils classified as light show superior initial removal, having a greater proportion of these components. However, just as the lighter oils would be expected to have some heavy components, it is likely that the medium and heavy oils also have some light components, *albeit* in lesser amounts. It is expected that such light components would be removed first. Eventually, both the light, medium and heavy oils would have more comparable medium and heavy components remaining. Therefore, the later removals become more equivalent in their effectiveness, as observed. Interestingly, these findings are in contrast with the results observed for oil pick-up from a glass surface, which shows higher pick-up, at early treatments, for heavier oils. This is probably related to the fact that the glass surface is quite different to a feather matrix. From a fundamental point of view this matter is worth exploring further, but is outside the scope of this thesis.

However, it is worth commenting upon the complexity of the effect of viscosity on oil sorption. It can be seen from the above that an increase in viscosity can lead to either an increase or a decrease in the efficacy of oil removal, depending upon the particular substrate. This is consistent with what has been suggested from previous study by Choi and Cloud (1992) that an increase in oil viscosity can result in two opposite effects. One the one hand it increases sorption thanks to the better adherence of the oil onto the material surface, on the other hand, it decreases sorption by reducing the penetration of the oil inside the materials. Therefore, it is not surprising that for feathers, where the substrate is quite micro-structurally complex, that more viscous oils are more resistant to removal leading to a preference for the lighter fractions being removed. On the other hand, a glass surface does not have such micro-structural complexity and the relative removal of lighter versus heavier components is expected to have a different basis rather than substrate penetration.

4.4.2.2 Comparison between oil and emulsion

The comparison of oil removal from duck feathers between oils and their respective emulsions is shown in Fig. 4.6.

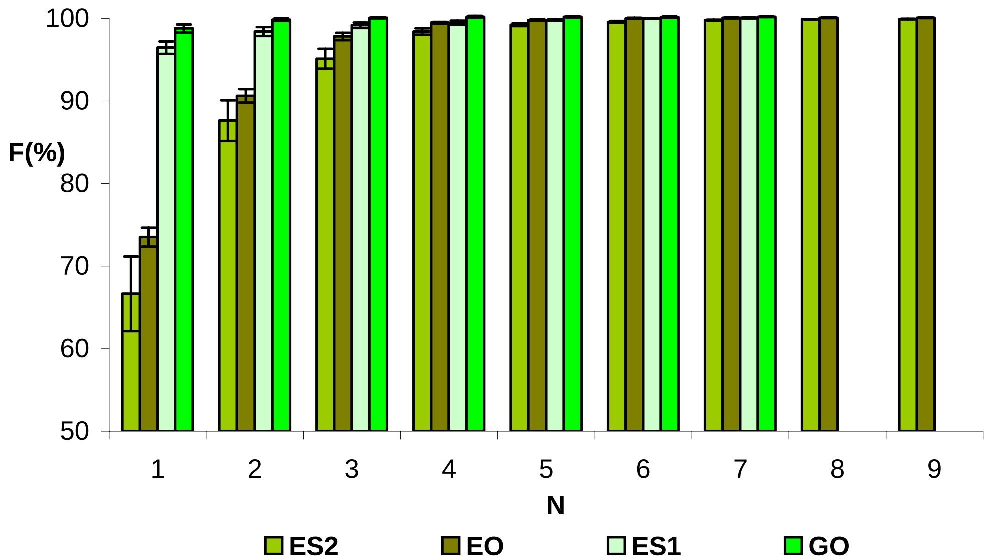


Figure 4.6: Comparison between oils and their respective emulsions for the pick-up, F (%), from duck feathers as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 13 in Appendix 4.1.

As can be seen, the removal for the early treatments is higher for oils than for their respective emulsions. For example, the initial removal for the heavy oil, EO, is 73.51%

compared to 66.66% for ES2. A similar, but less pronounced, outcome is observed for the light oil, GO, with initial removals of 98.78% and 96.46% respectively for GO and ES1. This is the reverse behaviour to the pick-up of these contaminant types from a glass surface. It was also observed that the difference in oil removal between oils and their respective emulsions becomes less pronounced as the number of treatments increases. Thus the maximum removal achieved is fairly comparable between the oils and their emulsions (at ca. 100% for both contaminant types; 7 - 9 treatments). These results are consistent with the purported higher viscosity of emulsions compared to their respective oils (IPIECA, 2001; Wei *et al.*, 2003; NOAA, 2004). *Vide supra* it was also suggested previously in this section that the more viscous the contaminant, the lower the pick-up from feathers.

4.4.2.3 Comparison amongst all contaminants

The comparison amongst all contaminants for their removal from duck feathers as a function of the number of treatments, N, is shown in Fig. 4.7.

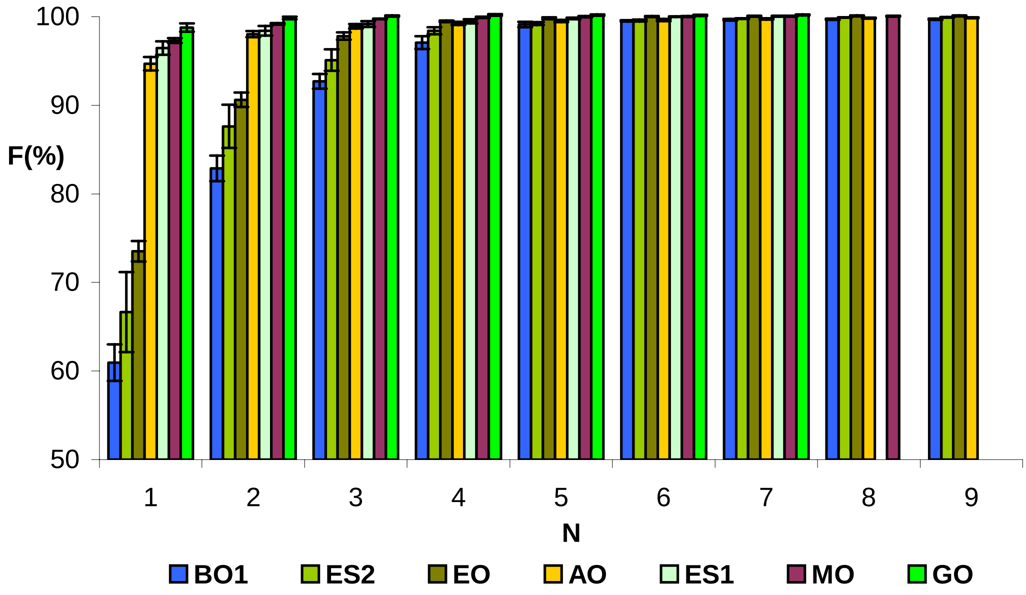


Figure 4.7: Comparison of the pick-up, F (%), from duck feathers as a function of the number of treatments, N, for all contaminants. Error bars represent the SE for five replicates. The data are presented in Table 14 in Appendix 4.1. Individual profiles of each contaminant are presented in Tables 5 to 11 in Appendix 4.1

Generally, for initial and early treatments there is considerable variation in oil removal. In particular, the initial pick-up is very different among the contaminants, ranging from

60.90% for BO1 to 98.78% for GO. However, beyond 5 treatments, all contaminants tested show comparable removals, approaching 100%. This indicates that the maximum removal of contaminant from duck feathers (for a defined number of treatments) appears to be independent of the nature of the contaminant.

4.4.3 Penguin feather clusters

Analogous experiments on the removal of the above contaminants were conducted on penguin feathers. The results of these experiments are given in Figs. 4.8 to 4.10.

4.4.3.1 Comparison amongst light, medium and heavy oil

The comparison of oil removal from penguin feathers amongst light, medium and heavy oils is presented in Fig. 4.8.

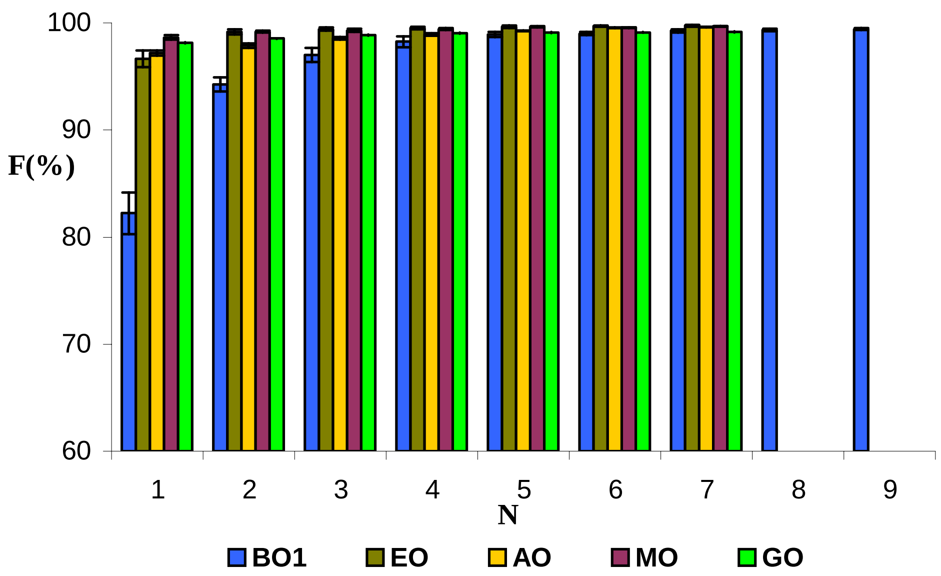


Figure 4.8: Comparison amongst light, medium and heavy oil for the pick-up, F (%), from penguin feathers as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 22 in Appendix 4.1.

As with duck feathers, the oil removal is found to be slightly higher for lighter oils (MO and GO) than for heavy oils (BO1) and, especially for the early treatments, Fig. 4.8. More specifically, the initial removal for MO is 98.46% compared to 82.23% for BO1 and 96.65% for EO. It was also observed that this difference becomes less pronounced as the number of treatments increases. Therefore, after 7 treatments the pick-up becomes comparable amongst the contaminants, approaching 100%. For example, the maximum pick-ups (after 7 and 9 treatments) are 99.68% and 99.41% for MO and BO1, respectively. As with duck feathers, the number of treatments needed to achieve a maximum removal depends on the specific contaminant and is less for lighter oils. In particular, this figure is 7 for MO compared to 9 for BO1. This again suggests that the removal efficiency is higher for light oils than for heavy oils even though their final removal efficacy is almost the same.

4.4.3.2 Comparison between oil and emulsion

As with duck feathers, it can be seen from Fig. 4.9 that the removal is higher for oils than for their respective emulsions. For example, the initial removal is 96.65% for EO, significantly higher than 88.98% for its emulsion (ES2). Similarly, the initial removal for GO is 98.12% compared to 94.86% for its emulsion (ES1). It was also observed that this difference becomes less pronounced as the number of treatments increases. Thus the maximum removal is 99.74% for EO, significantly higher than 99.04% for ES2, and similarly the respective figure for GO is 99.16%, comparable to 99.09% for ES1.

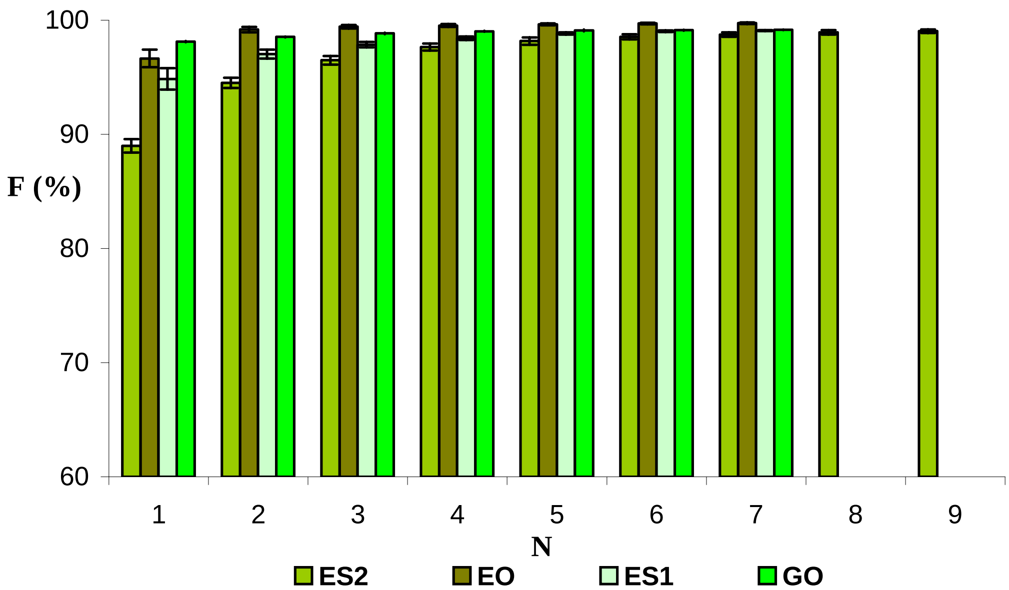


Figure 4.9: Comparison between oils and their respective emulsions for the pick-up, F (%), from penguin feathers as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 23 in Appendix 4.1.

4.4.3.3 Comparison amongst all contaminants

It can be seen from Fig. 4.10 that, generally, for initial and early treatments there is considerable variation in oil removal. In particular, the initial pick-up is very different amongst the contaminants, ranging from 82.8% for BO1 to 98.6% for GO. However, beyond 5 treatments, most contaminants tested show comparable removals, approaching 100%. This indicates that the maximum removal of contaminant from penguin feathers (for a defined number of treatments) is fairly independent of the nature of the contaminant. It is worth noting that generally, penguin feathers appear more resistant to cleansing than duck feathers. This will be discussed in Section 4.4.4 and in the subsequent chapters.

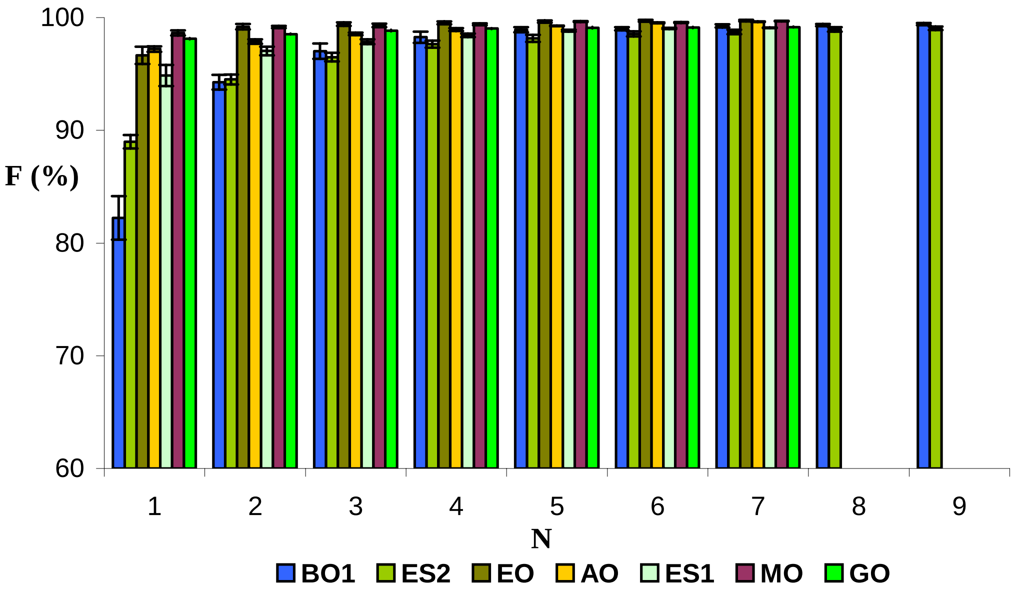
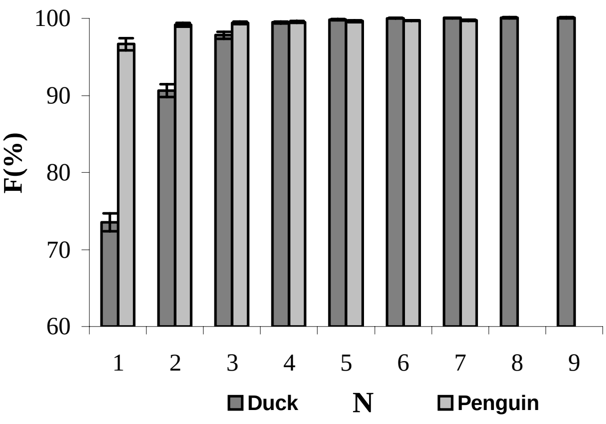


Figure 4.10: Comparison of the pick-up, F (%), from penguin feathers as a function of the number of treatments, N, for all contaminants. Error bars represent the SE for five replicates. The data are presented in Table 24 in Appendix 4.1. Individual profiles of each contaminant are presented in (Tables 15 to 21) in Appendix 4.1

4.4.4 Comparison of removal between duck and penguin feather clusters

4.4.4.1 Heavy oil and emulsion

It can be seen from Fig. 4.11 that at the first three treatments, for heavy oils such as BO1 and EO, the removal is higher for penguin feathers than for duck feathers. A similar outcome is also observed for the emulsion (ES2), Fig. 4.12. However, this distinction becomes less pronounced as the number of treatments increases. The maximum removal, although more comparable, becomes slightly higher for duck feathers than for penguin feathers.



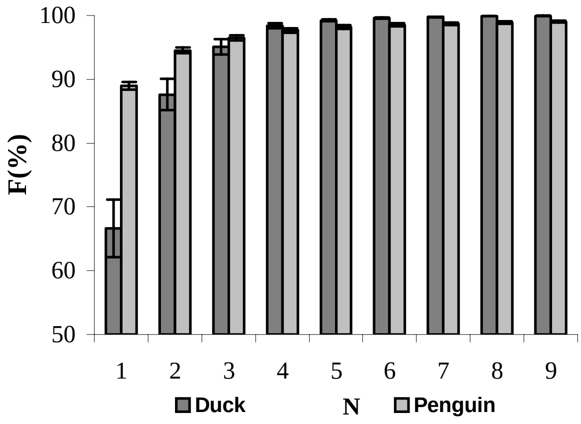
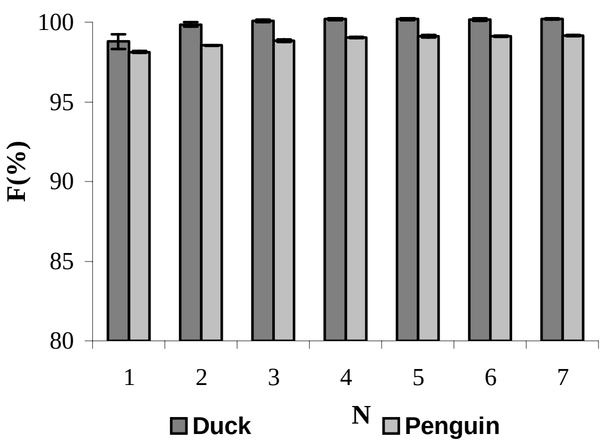


Figure 4.11: Comparison of the pick-up of heavy oil (EO) for duck and penguin feathers. Error bars represent the SE for five replicates. The data are presented in Table 25 in Appendix 4.1.

Figure 4.12: Comparison of the pick-up of heavy emulsion (ES2) for duck and penguin feathers. Error bars represent the SE for five replicates. The data are presented in Table 26 in Appendix 4.1.

4.4.4.2 Light oil and emulsion

The comparison of the pick-up between duck and penguin feathers for light oil and emulsion is shown in Figs. 4.13 and 4.14. It can be seen from Figs 4.13-4.14 that for both light oil and emulsion, the removal is higher for duck feathers than for penguin feathers for all treatments.



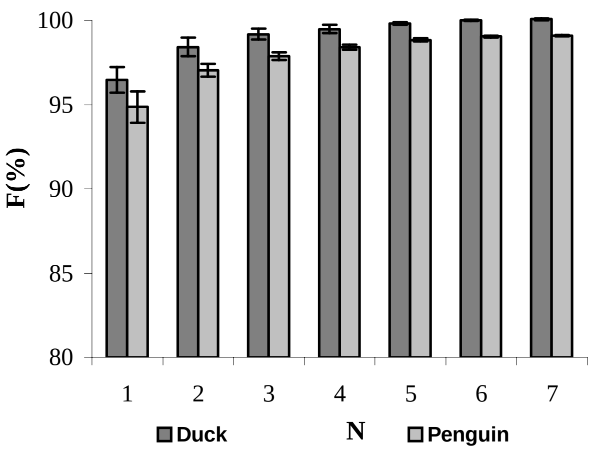


Figure 4.13: Comparison of the pick-up of light oil (GO) for duck and penguin feathers. Error bars represent the SE for five replicates. The data are presented in Table 27 in Appendix 4.1.

Figure 4.14: Comparison of the pick-up of light emulsion (ES1) for duck and penguin feathers. Error bars represent the SE for five replicates. The data are presented in Table 28 in Appendix 4.1.

Having demonstrated the efficacy of the optimal particles in the removal of contaminants from a glass substrate and from feather clusters, the next step was to apply this method to the plumage of whole bird models (carcasses).

4.5 Removal of fresh oil from a whole bird model

4.5.1 Preliminary tests on removal of fresh oil from plumage

It was decided that experiments on whole bird models (carcasses) should be conducted on dead birds prior to testing on live animals (Walraven, 1992). Therefore, a series of experiments has been carried out in order to explore the use of the optimal iron powder in the removal of a variety of contaminants from the feather plumage of penguin carcasses. Little Penguin (*Eudyptula minor*) carcasses were provided by the Phillip Island Nature Park, Melbourne, Australia. Their body weight ranged from 420 to 1880 g. The plumage of each carcass used for experimentation was established by visual inspection to be in good condition prior to use.

Several fresh oil contaminants, varying in viscosity (as mentioned previously in Section 4.3) have been employed, namely, Gippsland crude oil (GO), engine oil (EO) and engine oil/seawater emulsion (ES2). GO and EO were chosen since these two oils represent the lightest and the heaviest respectively of the range of oils employed so far in the experiments on feather clusters. Preliminary investigations were essential in order to ensure that the tare weight of carcasses had been satisfactorily stabilised.

4.5.2 Challenges relating to experiments on whole bird models

The carcasses that are used are stored frozen (at around - 20^{o}C). Therefore, it is necessary to thaw each carcass prior to use and to ensure that its weight is stabilized prior to gravimetric experiments. The weight stability of a thawed carcass may be affected in a number of ways. These have been identified as residual moisture on the plumage and orifice leakage. Obviously, material residues are also removed from the carcass by brushing. In previous successful studies on carcasses (Ngeh, 2002) a procedure for residual moisture was to simply dab the carcasses with tissue after overnight thawing at room temperature. To prevent orifice leakage, the head and rear end of the carcass was sealed with plastic bags after thawing and draining, Fig. 1 in Appendix 4.2. To ensure that these techniques were effective, the weight of each carcass was monitored over time. In some cases, it was found that the above procedures were not satisfactory in establishing a constant weight. Controlled experiments (Fig. 2, Appendix 4.2) indicated that, in spite of attempts to dry the plumage by dabbing with tissue, some carcasses could still lose up to ca. 1.6% of the total body weight in moisture when placed in an oven (ca. 35 ^{o}C) for a period of time (ca. 15 h). Therefore, the final procedure for establishing a constant weight of a carcass also involved warming overnight in an oven set at ca. 35 ^{o}C. The weight of the carcass was monitored to establish a constant weight.

4.5.3 Removal of fresh oil from plumage

Having established a method for stabilizing the weight of a carcass, experiments were implemented to investigate the efficacy of removal of different contaminants from plumage. As with the experiments on feather clusters, it was considered desirable that the experiments on whole bird models (carcasses) be done in five-fold replicates. However, due to the limited availability of carcasses, it was necessary to adopt a previously developed methodology (Orbell *et al*., 2004) whereby five replicates were performed on the same carcass by, judiciously, patching the oil onto the plumage.

Four fresh crude oils (the same oils employed in Sections 4.2 and 4.4), namely GO, AO, EO and BO1 were considered with respect to their removal from plumage. This choice ensured a range of contaminants, from light to medium to heavy. Also, the bunker oil chosen (which is very heavy) is of the same type that has been found to occur at Phillip Island, posing a threat to the colony of Little Penguins (*Eudyptula minor*) (Healy, *personal communication*). For these contaminants the patch (five-fold) experiments were implemented for up to 10 treatments. The method for determining contaminant removal from plumage is described in Section 2.1.3 was used. The comparative results for the above contaminants are presented in Fig. 4.15.

As can be seen from Fig. 4.15, the initial removal tends to be higher for lighter oils than for heavy ones. For example, for the initial treatment, removal is 41.4% for GO compared to 35.1% for BO1. However, the maximum removal is comparable after 10 treatments, being in the range 96.0 - 97.6%. Specifically, a maximum removal of 97.6%

for the lightest oil, GO, is attained, compared to 96.0% and 97.0% for the heavy oils, BO1 and EO, respectively. The medium oil, AO, has a maximum removal of 97.1%.

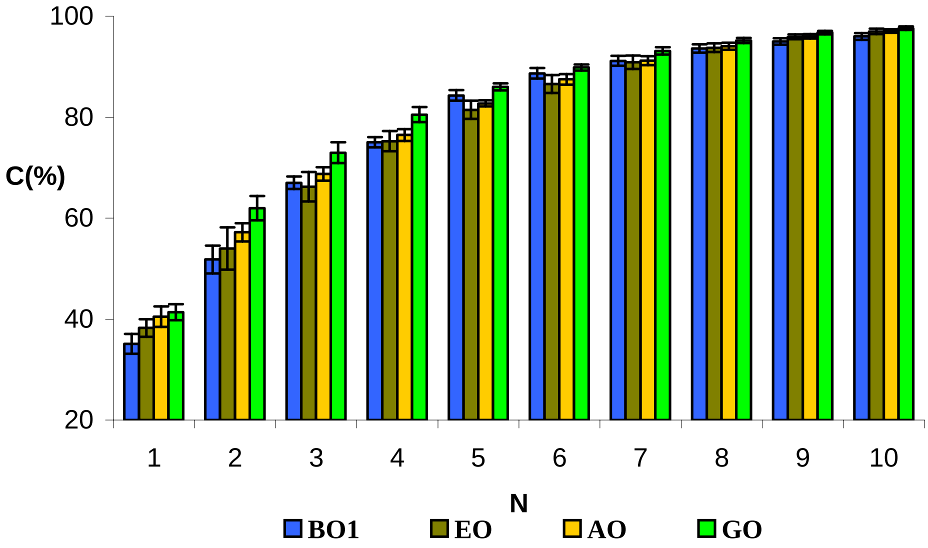


Figure 4.15: Comparison amongst various fresh oils for their pick-ups, C (%), from carcasses as a function of the number of treatments, N. Error bars represent the SE for five replicates (patch experiments). The data are presented in Table 5 in Appendix 4.2. Individual profiles for each contaminant are presented in Tables 1 to 4 in Appendix 4.2.

4.6 Comparison of removal between feather clusters and plumage

As explained in the previous section, four fresh oils, namely GO, AO, EO and BO1 only were employed for the experiments on the penguin carcasses. Therefore, comparisons of the removal between penguin feather clusters and penguin plumage were made for these contaminants only. The comparative data are shown in Figs. 4.16 to 4.19.

In general, irrespective of the number of treatments, the removal is lower for plumage than for feather clusters, Figs. 4.16 to 4.19. In particular, the initial removal is significantly lower for plumage than for clusters**.** However, the difference becomes less pronounced as the number of treatments increases. The maximum removal, although more comparable, is still lower for plumage than for feather clusters.

Specifically, for GO, Fig. 4.16, the initial removal from the plumage is 41.4% - much lower than 98.1% for the feather clusters. The maximum removal is 97.6% for the plumage, lower than 99.2% for the feather clusters. Similarly, for AO, Fig. 4.17, the initial removals are 40.5% and 97.2% for plumage and feather clusters, respectively. The maximum removals are 97.1% for the former and 99.6 % for the latter.

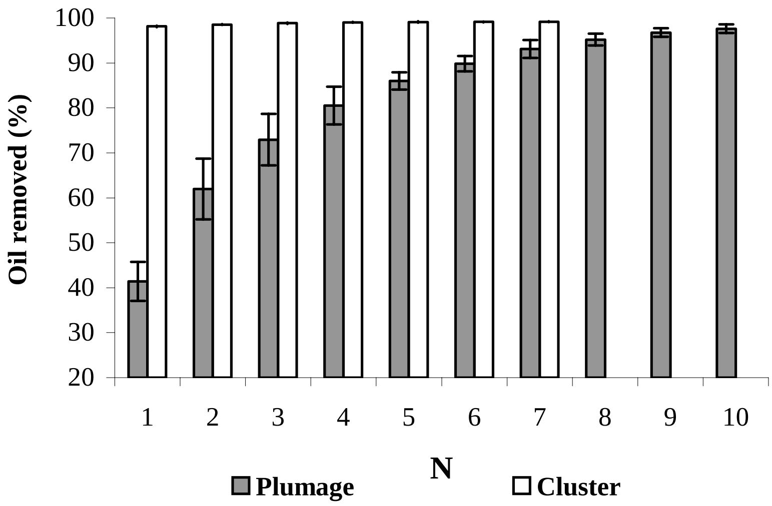


Figure 4.16: Comparison between penguin feather clusters and penguin carcass plumage for the removal of GO as a function of the number of treatments, N. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 6 in Appendix 4.2.

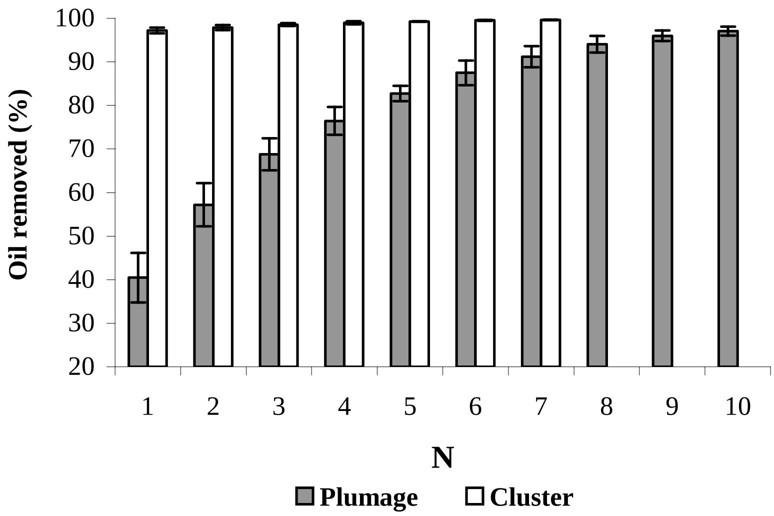


Figure 4.17: Comparison between penguin feather clusters and penguin carcass plumage for the removal of AO as a function of the number of treatments, N. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 7 in Appendix 4.2.

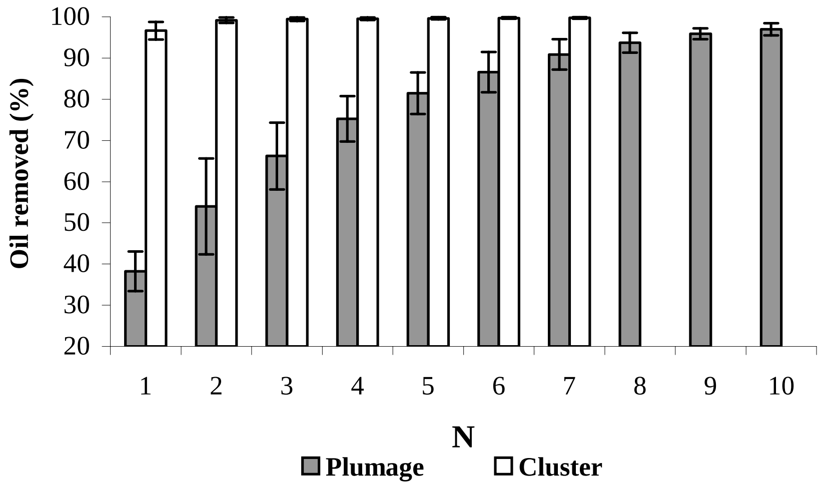


Figure 4.18: Comparison between penguin feather clusters and penguin carcass plumage for the removal of EO as a function of the number of treatments, N. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 8 in Appendix 4.2.

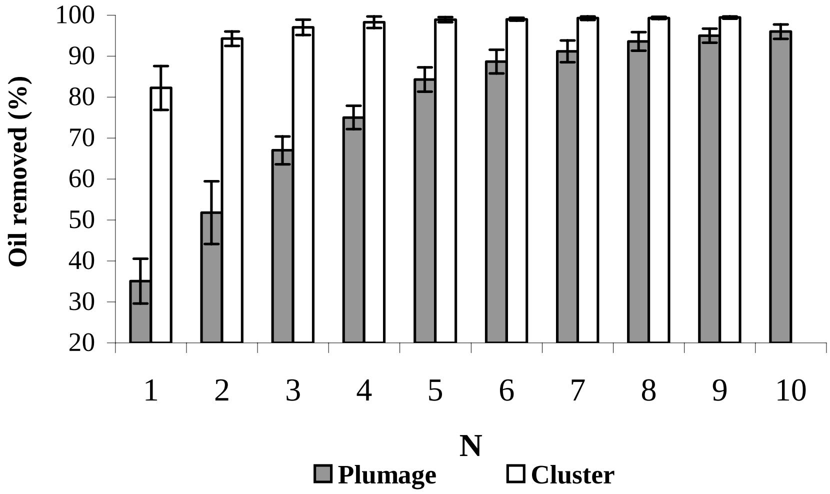


Figure 4.19: Comparison between penguin feather clusters and penguin carcass plumage for the removal of BO1 as a function of the number of treatments, N. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 9 in Appendix 4.2.

With respect to EO, it can be seen from Fig. 4.18 that the initial removals are 38.2% and 96.7% for the plumage and the feather clusters, respectively. The maximum removal is 97.0% for the plumage, considerably lower than 99.7% for the feather clusters. Finally, for BO1, Fig. 4.19, the initial removal from the plumage is 35.1%, considerably lower than 82.2% for the feather clusters. The final removal is 96% for the plumage, lower than 99.4% for the feather clusters.

The difference in oil removal profiles of feather clusters compared to plumage is understandable since the individual feathers of feather clusters are more accessible than those of plumage. This raises the possibility of improving initial removal from plumage by pre-agitating the feathers. This aspect has not been explored in this thesis but is a consideration for field application.

4.7 Comparison of maximum removal between glass and feathers

Since oil removal from a glass surface is assessed on the basis particle-to-oil ratio, and the removal of oil from feather clusters is determined on the basis of the number of treatments, comparisons can only be made with respect to maximum removals.

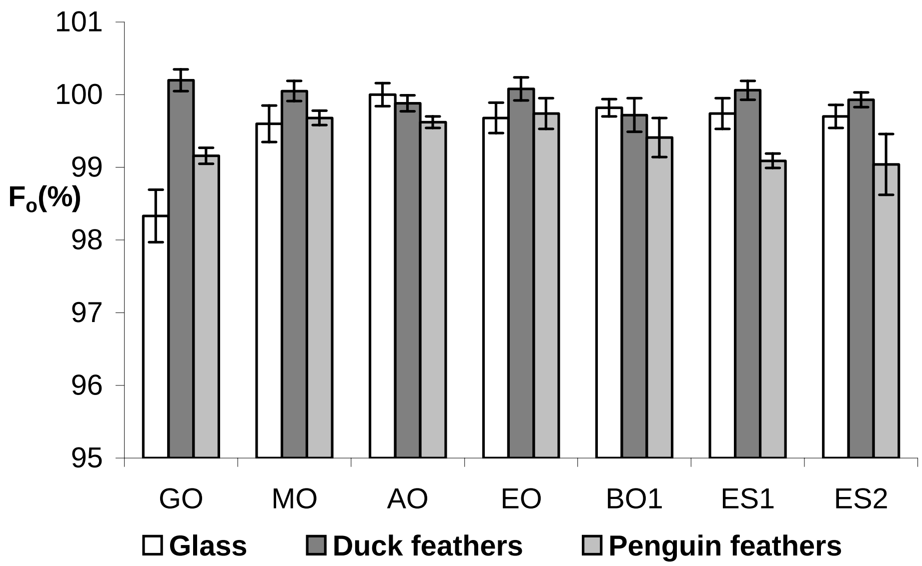


Figure 4.20: Comparison amongst glass, duck feather clusters and penguin feather clusters for the maximum removal for different crude oils and emulsions. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 10 in Appendix 4.2.

As can be seen in Fig. 4.20 the maximum removal is, in general, higher in the case of duck feathers, than for glass and penguin feathers. However, a removal exceeding 99% is achievable for all contaminants and for all substrates (glass, duck and penguin feathers), except for the GO (98.3%) in the case of glass. In the latter case, a component of this oil appears to adhere to the surface and is resistant to removal, *vide supra*.

4.8 Comparing removal efficiency for different contaminants using an empirical model

An empirical model adapted from Ngeh (2002) was employed to model the ad(b)sorption isotherms. This would give an indication of the relative *overall* efficiency of oil pick-up from feathers or from a glass surface. An empirical equation that can be used to fit the typical contaminant uptake curve is:

$$F = F_o(1 - e^{-kN}) \qquad (4.2)$$

Where F and N are the extent of removal and the number of treatments respectively[1]. F_o is the maximum value of F, and k is a constant that determines how effectively the asymptote value F_o is approached. Equation (4.2) can be rearranged to give

$$- \ln(1-F/F_o) = kN \qquad (4.3)$$

Clearly, the greater the value of k, the greater is the efficiency for the oil removal (Ngeh, 2002). Equation (4.2) can be differentiated to give equations (4.4) and (4.5).

$$dF/dN = F_o k e^{-kN} \qquad (4.4)$$

$$(dF/dN)_{N=0} = F_o k \qquad (4.5)$$

As with k itself, the product $F_o k$ may be taken as indicative of the efficiency of contaminant removal and may be used to establish the relative order of removal efficiencies of different contaminants (Ngeh, 2002). A plot of $-\ln(1 - F/F_o)$ versus N for the respective removal of EO from duck feathers is shown in Fig. 4.21. Similar plots for other contaminants are presented in Appendix 4.2.

[1] In case of oil removal from a glass surface, N is replaced by R (particle-to-contaminant ratio) in Equations 4.2 – 4.5.

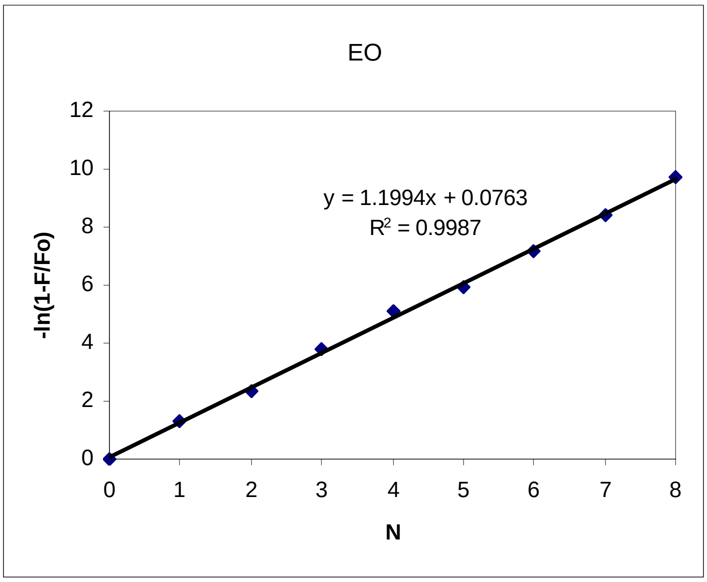


Figure 4.21: Plot of -ln(1-F/F_o) versus the number of treatments, N, for the removal efficiency of EO from duck feathers.

Values of the slope, k, determined from liner regression analyses, and the product kF_o for seven different contaminants for duck and penguin feathers and glass are listed in Table 4.1.

Table 4.1: Values of k and kF_o for the removal of contaminants from duck and penguin feathers and glass.

Contaminants	**Viscosity (cSt)**	**Duck feathers**		**Penguin feathers**		**Glass**	
		k	kFo	k	kFo	k	kFo
GO	1.42	1.30	129.96	1.10	108.55	0.35	34.05
ES1	-	1.03	103.38	1.05	104.20	0.52	52.23
MO	4.13	1.27	126.60	0.96	95.94	0.33	32.52
AO	50.10	0.82	82.08	0.93	92.24	0.53	52.81
EO	307.13	1.20	120.04	1.17	116.77	0.56	55.82
ES2	-	1.02	101.94	0.72	71.64	0.84	83.31
BO1	180	1.14	113.95	0.82	81.71	0.59	59.04

As can be seen from Table 4.1, for feathers (duck and penguin feathers), the values of k and kF_o are, in general, higher for lighter contaminants such as GO and MO than for heavier contaminants such as AO and BO1. This indicates that the removal of lighter contaminants from feathers is more efficient than that of heavier contaminants. However, for glass the opposite is found to be true. In other words, the removal efficiency from petri dish is, in general, higher for heavier contaminants such as EO and BO1 than for lighter contaminants such as GO and MO. It was also found that for duck and penguin feathers the removal efficiency is higher for oils than for their respective emulsions and *vice versa* for a petri dish. These findings are consistent with the observations made in the previous sections relating to the removal efficacy of contaminants.

4.9 Comparing removal efficiency for different substrates (matrices) using an empirical model

In order to compare the efficiency of the removal of different contaminants from duck feathers, penguin feathers and a glass substrate, a novel method for comparing parameters on x and y axes in the present work has been adapted from that developed by Bigger *et al.* (2001), for comparing the effects of additives in polymers. This method was also employed in other studies (Ngeh, 2002). Plots of kF_o (duck feathers) versus kF_o (penguin feathers), kF_o (duck feathers) versus kF_o (glass), kF_o (penguin feathers) versus kF_o (glass) is shown in Fig. 4.22. In this plot, the oblique line where kF_o (duck feathers) = kF_o (penguin feathers), represents data pairs where there is no difference in the efficiency of oil pick-up between duck and penguin feathers. A similar line of unit gradient can be drawn, for the comparison between duck feathers and glass, and between penguin feathers and petri dish. The regions above and below this line are regions where the efficiency of oil removal is greater for duck or penguin feathers respectively. The perpendicular distance of a given point from the oblique line indicates the magnitude of the difference and this, when used in conjunction with co-ordinates of the point, enables a comparison of the relative efficiencies to be made. Furthermore, the method enables systems of high and/or low efficiencies to be readily identified. Clearly, the points that lie furthest from the origin correspond to systems of highest efficiencies (Ngeh, 2002).

It can be seen from Fig. 4.22 that for all contaminants tested the removal of oil from duck feathers is more efficient than the removal from petri dish as the corresponding points lie in the region above the oblique line. For most contaminants tested, except AO, the removal of oil from duck feathers is more efficient than the removal from penguin feathers as the corresponding points lie in the region above the oblique line. However, for ES1, there is little difference in the removal efficiency from duck and penguin feathers as the corresponding point lies just on the oblique line. Regarding the removal efficiency between penguin feathers and glass, the removal is more efficient from penguin feathers than from glass for most contaminants tested, with the exception of ES2 that shows the opposite.

The kF_o values for duck feathers are furthest from the origin suggesting that for all three matrices, the removal efficiency for duck feathers is the highest, followed by penguin feathers and glass.

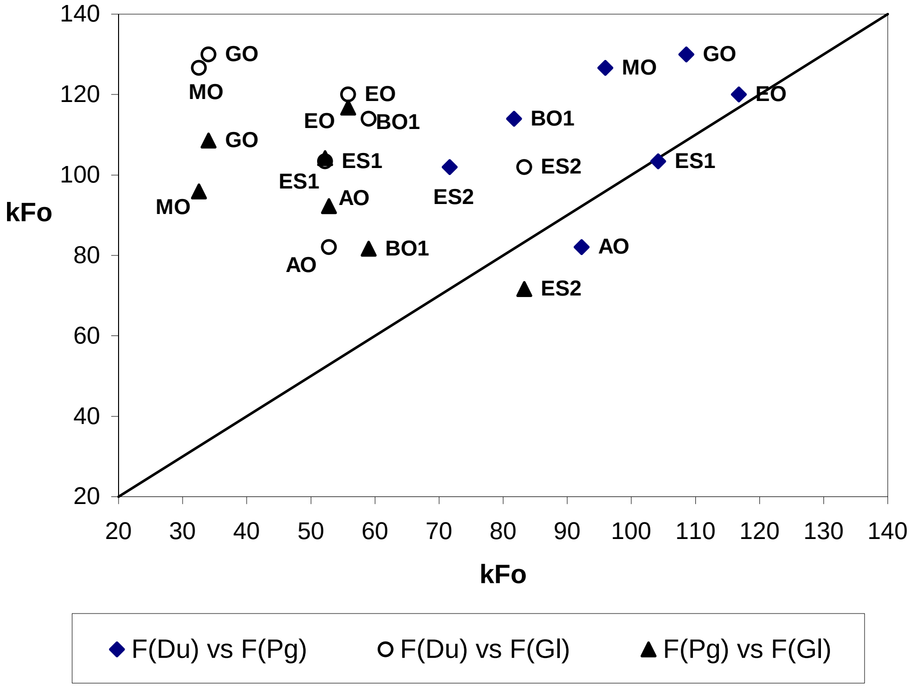


Figure 4.22: Comparison of the efficiency of oil removal for glass, duck feather clusters and penguin feather clusters. The symbols F(Du), F(Pg) and F(Gl) are the removal efficiencies from duck feathers, penguin feathers and glass, respectively. The letters AO, BO1, EO, ES1, ES2, GO and MO denote Arab medium crude oil, bunker oil 1, engine oil, emulsion1, emulsion2, Gippsland crude oil and Merinie crude oil.

4.10 Conclusions

The optimal iron powder identified previously was applied to the removal of various types of fresh contaminants from glass, duck and penguin feather clusters, as well as penguin plumage.

Firstly, the different grades of iron powder were tested on the removal of seven different oils and emulsions, ranging from light, to medium to heavy, from glass. In general, it was found that the removal increases with increasing the viscosity of contaminant. In particular, the initial removal is significantly higher for heavier oils than for light oils. The maximum removals are comparable being slightly higher for heavy oils than for light oils. It was also evident that the pick-up, especially the initial pick-up is higher for emulsions than for their corresponding oils. However, regardless of the ratio, R, a final removal of ca. 100% from glass is achieved for all contaminants with the exception of the light crude oil (GO).

A number of blank tests have been carried out to investigate whether a correction had to be made in the gravimetric methodology to account for the removal of natural feather oils (preening oils). It was found that the possible removal of preening oil was insignificant in the context of these experiments. Therefore, it was deemed unnecessary to make systematic blank corrections for the experiments conducted in this thesis. The current method does not enable to be answered the question of whether preening oil(s) are actually removed by magnetic cleansing.

The optimal iron powder and contaminant were employed for experiments on duck feather clusters and, interestingly, the pick-up is found to increase as the viscosity decreases, which is opposite to the results for glass experiments. In particular, the initial removal is much higher for lighter oils than for heavier ones. It was also observed that the difference becomes less pronounced as the number of treatments increases. Thus, as with a glass substrate, the maximum pick-up becomes more comparable for both light and heavy contaminants. It was also observed that the pick-up for oils tends to be higher than that of their corresponding emulsions especially for the first treatment. Again, this result is contrary to the outcome obtained from experiments on oil removal from glass. However, regardless of the number of treatments required to achieve a maximum removal, ca. 100% removal from the duck feathers is achieved for all the oils and emulsions tested.

The removal of the same oils and emulsions from penguin feather clusters, using the optimum magnetic particle grade was also investigated. Consistent with duck feathers, the initial pick-up increases as the viscosity decreases, which is opposite to the outcome for glass, and there is little difference in the final pick-up between all of the contaminants. However, it was also noted that the difference in oil removal between light and heavy oils for the penguin feathers is not as pronounced as that for the duck feathers. It was also observed that the pick-up for oils is higher than that for their corresponding emulsions, similar to the results from duck feathers, and contrary to what is observed for removal from glass. Regardless of the number of treatments needed to achieve maximum removal, approaching 100% removal from penguin feathers is achieved for most of the oils and emulsions tested. It is important to emphasize that a removal of ca. 100% for heavy oils such as bunker oil and engine oil is an important outcome since these contaminants are considered to be very difficult to remove using the conventional techniques and usually need a pre-treatment (conditioning) agent.

A comparison of oil removal was also made between duck and penguin feathers. It was found that for light oils and emulsions, removals are higher for the duck feathers than for the penguin feathers at all levels of treatment. For heavy oils and emulsions, the pick-ups are found to be higher from the penguin feathers than from the duck feathers for the first three treatments, and this difference becomes less pronounced as the number of treatments increases. The maximum removal, although more comparable, becomes slightly higher for duck feathers than for penguin feathers.

By comparing the maximum oil removal from a glass surface, duck and penguin feather clusters, it was evident that a higher removal is achieved for duck feathers, than for glass and penguin feathers, and exceeded 99.1% for all contaminants tested except for the case of the removal of light crude oil (GO) from glass where a ca. 1.7% residual remained on the glass.

An adapted empirical model was used to compare the removal efficiency of different contaminants. It was found that for duck and penguin feathers the removal efficiency is higher in the case of light oils than heavy oils, however, the opposite is true for glass. It was also observed that the removal of oils from feathers is more efficient than that of their respective emulsions, and *vice versa* for glass. These findings are consistent with observations regarding the removal efficacy of contaminants, indicating that the use of the empirical model in measuring removal efficiencies is reliable and effective.

A graphic method was adapted to compare the removal efficiency of different contaminants between duck feathers, penguin feathers and glass. It was found that, for all contaminants the removal of contaminants for duck feathers is, in general, the most efficient, followed by penguin feathers and glass.

Experiments were conducted on the removal of contaminants from whole bird models (carcasses). The optimal grade of iron powder and four contaminants, namely GO, AO, EO and BO1 have been employed in these experiments. Reflecting the results on feather clusters, it was found here that the removal appears to be higher for the less viscous oil. For each of the contaminants tested, the initial removal is significantly lower from the plumage than from the feather clusters, although this difference becomes less pronounced as the number of treatments increases. The maximum pick-up ranges from 96.0 - 97.6%. Although very promising, this is still considerably lower than that of the feather clusters. This also illustrates the complexity of experiments on whole bird models. It is likely that this removal could be significantly enhanced by suitable plumage agitation and/or the appropriate use of preconditioning.

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CHAPTER 5: APPLICATION OF THE OPTIMAL GRADE OF MAGNETIC PARTICLES TO THE REMOVAL OF *TARRY* CONTAMINATION FROM FEATHERS

CHAPTER 5: APPLICATION OF THE OPTIMAL GRADE OF MAGNETIC PARTICLES TO THE REMOVAL OF *TARRY* CONTAMINATION FROM FEATHERS

5.1 Introduction

Contamination with oil that is considered 'fresh', i.e. free flowing, non-weathered or non-tarry, has been the subject of environmental remediation and wildlife rehabilitation research for a long time (Smith, 1983; Jenssen, 1994; Suni *et al.*, 2004). However, contamination can also be weathered or highly viscous and tarry (Welte and Frink, 1991; Walraven, 1992; Hill, 1999; Holcomb and Russell, 1999, OWCN, 1999; 2003; USFWS, 2002, Bryndza *et al.*, 2005). This presents additional challenges to both environmental remediation and oiled wildlife treatment (Holcomb and Russell, 1999; Bryndza *et al.*, 2005). There are also other factors to consider. For example, temperature may affect oil sorption (removal) from water (Johnson *et al.*, 1973; Choi and Cloud, 1992; Aisien *et al.*, 2003; Toyoda *et al.*, 2000; Haussard *et al.*, 2003; Sayed *et al.*, 2003; 2004; Duong and Burford, 2006), from soil (Urum *et al.*, 2004; 2005), and particularly from feathers (Berkner *et al.*, 1977). Indeed it has been suggested by Berkner *et al.* (1977) that oil removal from feathers is dependent on the temperature of the cleaning agents used and that higher temperatures result in better cleaning efficiencies. It was also documented (Berkner *et al.*, 1977) that viscous (tarry) oil can only be removed from feathers by using very hot cleaning agents (solvent). Similarly, the effect of the temperature of flushing water on the oil removal efficiency of shoreline cleaning agents was also observed (Tumeo and Cote, 1998). Therefore, in the battle against tarry contamination of feathers or fur, temperature would be expected to play a very important role. Although magnetic particle technology proves to be effective at removing a variety of fresh oils and their corresponding emulsions (Orbell *et al.*, 1999; 2004), it has been suggested (Copley, 1999; Hill, 1999) that tarry or highly viscous oil contamination might prove resistant to the application of the so-called 'magnetic cleansing' method.

For the above reasons, temperature dependent *in vitro* studies were performed to test the ability of the optimal iron powder to magnetically cleanse a highly viscous (tarry) oil from feather clusters of both the Mallard Duck (*Anas platyrhynchos*) and the Little Penguin (*Eudyptula minor*) and from the feather plumage of Little Penguin carcasses. In addition, the thermodynamics of the magnetic tarry oil removal process has also been investigated in order to provide an insight into the phenomenon.

5.2 Temperature dependency in the removal of tarry contamination from feather clusters

5.2.1 Duck feathers

The contaminant used is Shell crude oil (SO) that is solid at room temperature and has a viscosity of 3000 - 4000 cSt at 100 ºC (Shell Company of Australia Ltd, 1999). This contaminant has been chosen to represent a "worst-case scenario" of tarry contamination, similar to that often encountered in the wild. Pre-weighed duck feather clusters, each consisting of four individual feathers tied together at the base, were immersed into the molten oil (ca. 28 ºC). Each cluster was then removed and the oil was allowed to solidify as a tarry deposit at room temperature (ca. 295 K) for about 15 min. It was observed that the tarry oil quickly solidified on the clusters after about 10 min. The contaminated feathers were then removed to a temperature-controlled room where they were left for another 30 min to achieve equilibrium. A series of ambient temperatures within the range 10 to 28 ºC was used. At each temperature, iron powder was applied to the contamination and magnetically harvested in accordance with a previously described protocol (Orbell *et al.*, 1999). For each cluster of duck feathers, ten treatments were required to achieve maximum removal, the percentage removal of contaminant for each treatment being determined gravimetrically. In this work, the first removal is defined as the removal at treatment one and the final pick-up is the result after ten treatments.

The temperatures at which these experiments were conducted are: 11.0, 12.2, 14.0, 15.5, 17.3, 20.2, 22.4, 25.5 and 27.5 ºC. For each five-replicate experiment, the temperature was measured three times during the course of the experiment; at the beginning, in-between and at the end. The temperature readings and their associated values are given in Table 1 in Appendix 5.1.

The percentage of oil removal from duck feather clusters versus temperature for treatments ranging from 1 to 10 is plotted in Fig. 5.1, and the 3D presentation of removal as a function of the ambient temperature is presented in Fig. 5.2.

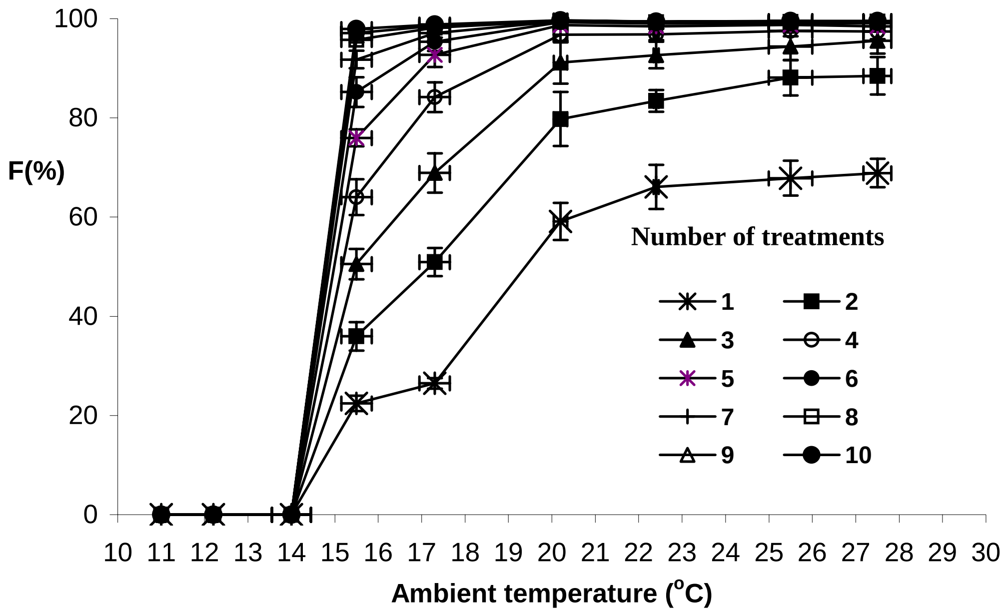

Figure 5.1: The removal of tarry contamination from duck feathers, F (%), for all treatments is represented as a function of ambient temperatures from 11 to 27.5 ºC. Vertical error bars represent the SE for five replicates. Horizontal error bars represent the standard deviation for ambient temperature. The data are presented in Table 2 in Appendix 5.1. Individual profiles for each temperature experiments are documented in Tables 3 to 8 in Appendix 5.1.

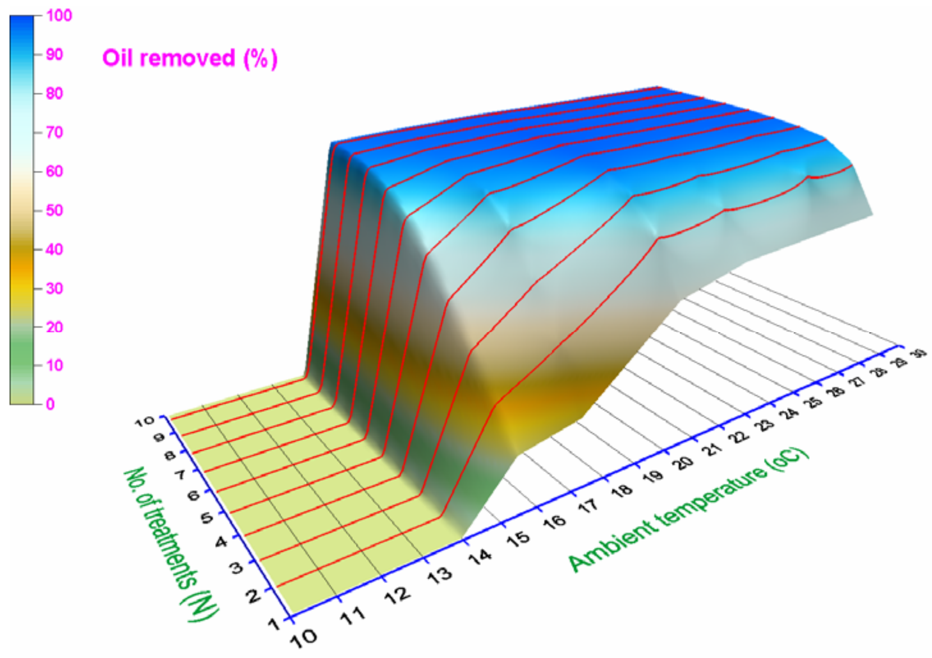

Figure 5.2: The 3D presentation of oil removal from duck feather clusters as a function of the ambient temperature.

It can be seen from Fig. 5.1 that for temperatures at or below 14 ºC such as at 11.0; 12.2 and 14.0 ºC, very little removal can be achieved, irrespective of the number of treatments. However, at temperatures above this, a dramatic removal starts to occur, and this temperature is found to be well below the pour point of the oil. These results are very encouraging with respect to the potential application of this technology to the treatment and rehabilitation of oiled wildlife, since they indicate that tarry contamination can be removed under conditions that are benign to birds *(*Baudinette *et al.*, 1986). Notably, for 10 treatments at ca. 15.5 ºC, a removal of 97.9% is achieved. It is remarkable that this phenomenon occurs within a temperature range of only ca. 1.5 ºC and that such a high removal is achieved for this sort of contaminant.

It may also be observed that, above the temperature at which a dramatic increase in removal is observed, the lower the number of treatments the more temperature-dependent is the percentage removal. For instance after one treatment a removal of 24.6% and 68.9% is obtained at ca. 15.5 ºC and 27.5 ºC, respectively, and after ten treatments the figures are 97.9% for ca. 15.5 ºC and 99.6% for 27.5 ºC.

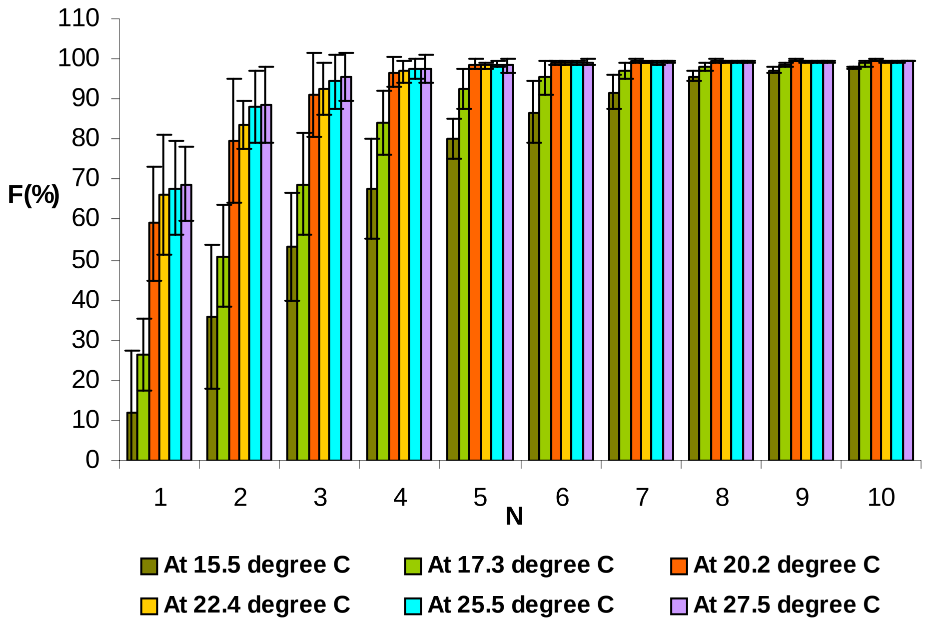

Figure 5.3: Histogram of the percentage, F (%), of tarry oil removed from duck feather clusters as a function of the number of treatments, N, for temperatures above the ‘acute’ temperature. Error bars represent the CV for five replicates. The data are presented in Table 9 in Appendix 5.1.

It was also observed that, the removal becomes much more reproducible as the number of treatments increases, as shown in Fig. 5.3. For example, the percentage uncertainties for these data, with respect to the CV, ranges from 9 - 15% for one treatment, 1 - 5% for five treatments and, notably, for the maximum number of treatments where ca. 100% removal is effectively achieved, the experiments are highly reproducible, with the percentage uncertainty ranging from 0.2 - 0.6%.

Clusters of duck feathers that have been contaminated with the tarry residue and subsequently cleansed with the magnetic particles are shown in Fig. 5.4.

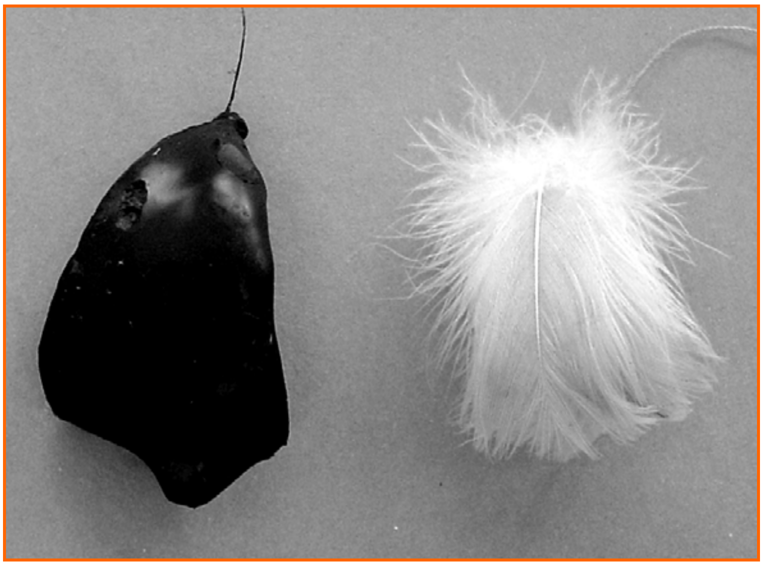

Figure 5.4: Clusters of duck feathers contaminated with tarry oil (left) and magnetically cleansed of tarry oil after ten treatments (right) at a temperature of about 23 ºC.

5.2.2 Penguin feathers

In order to see whether this effect occurs for other type of feathers, similar experiments were conducted on penguin feather clusters that were contaminated with the same tarry residue. These feathers were chosen since they are quite different in their microstructure to duck feathers. The experimental details and methodology were basically similar to those for the duck feathers discussed in the previous section. However, unlike the duck feather experiments that were carried out in five-fold replicate, these tests were performed once only. The temperatures at which the experiments were conducted were: 11.0, 12.2, 14.0, 15.0, 16.2, 18.5, 23.0 and 27.0 ºC. The temperature readings and their associated values are given in Table 10 in Appendix 5.1. A similar set of curves to the duck feather experiments is obtained, Fig. 5.5.

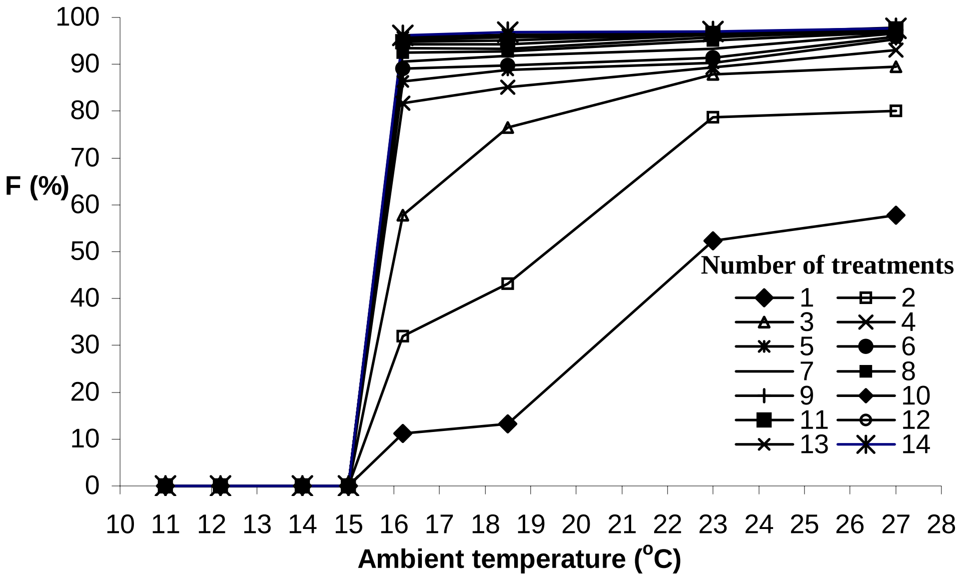

Figure 5.5: The magnetic removal of tarry contamination from penguin feathers for all treatments is represented as a function of eight different ambient temperatures from 11 to 27 ºC. The standard deviation of the ambient temperature ranges from 0.1 to 0.4 ºC. The data are presented in Table 11 in Appendix 5.1. Individual profiles are documented in Table 12 in Appendix 5.1.

It can be seen from Fig. 5.5 that for temperatures at or below 15.0 ºC such as 11.0, 12.0, 14.0, and 15.0 ºC, very little removal can be achieved, irrespective of the number of treatments. However, at temperatures above this, a dramatic removal starts to occur. Again, this phenomenon occurs within a temperature range of only ca. 1.2 ºC and such a high removal is achieved for this sort of contaminant. It is also noticed that, above the temperature at which a dramatic increase in removal is observed, the lower the number of treatments the more temperature-dependent is the percentage removal. For instance after one treatment a removal of 11.3% and 57.9% is obtained at 16.2 and 27 ºC, respectively, and after fourteen treatments the figures are 96.1% for 16.2 ºC and 97.7% for 27.0 ºC.

Fig. 5.6 compares duck and penguin feather clusters for the removal of tarry oil at the final treatment (N = 10 and N = 14 respectively) as a function of the ambient temperature. For duck and penguin feathers, at temperatures at or below ca. 14 ºC and ca. 15 ºC respectively, a negligible amount of contaminant is removed. When the dramatic removal is evident, over and above these temperatures, the removal for duck feathers at ca. 98% (at 15.5 ºC) is greater than that for penguin feathers at ca. 96% (at 16.2 ºC). Consequently, the maximum percentage removal achieved at the respective temperatures of 27.5 ºC and 27.0 ºC is ca. 100% and ca. 98% respectively. These values are found to be significantly different at the 95% confidence level. It is possible that, within experimental error, the temperature at which a dramatic removal starts to occur is the same for both feather types.

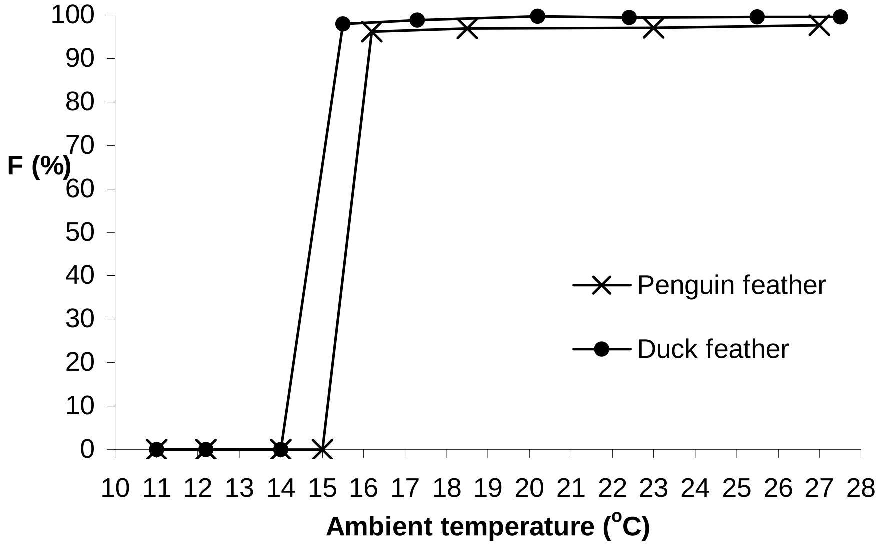

Figure 5.6: A comparison between duck and penguin feather clusters for the removal of tarry oil at the final treatment (ten and fourteen treatments respectively) as a function of the ambient temperature. Error bars are omitted for clarity. The data are presented in Table 13 in Appendix 5.1.

5.3 Temperature dependency in the removal of tarry contamination from plumage

Temperature dependency studies were also conducted with respect to oil removal from plumage. Penguin carcasses (*Eudyptula minor*) were carefully prepared for gravimetric experiments, as described previously (Section 4.5). The same tarry oil was melted (pour point ca. 28 ºC) and applied as a patch to the breast feathers of the carcass. Each oiled carcass was left for 30 min in a temperature-controlled room to equilibrate, in turn, to a series of ambient temperatures within the range 10 to 26.4 ºC. The temperatures used in the subsequent experiments were 10.0; 12.0; 14.0; 16.3; 18.4; 20.1; 22.4; 24.2 and 26.4ºC. These temperatures are the means for three measurements made at each ambient temperature taken over the course of each experiment; the full data are provided in Table

14, Appendix 5.1. At each temperature, iron powder was applied to the contaminant and magnetically harvested (Orbell *et al.,* 1999). For each carcass, nine treatments were required to achieve maximum removal, the percentage removal for each contaminant being determined gravimetrically. All experiments were conducted in five-fold replicate (patch-wise). The acute temperature dependency observed for the removal of tarry residue from duck and penguin feather clusters is also observed for feather plumage, Fig. 5.7._ It may be seen that, at or below ca. 14.0 ºC, very little removal can be achieved, irrespective of the number of treatments. The resistance to oil removal at temperatures less that or at ca. 14.0 ºC persists even when the surface of the deposit is agitated using a spatula and/or followed by rubbing iron powder into the surface. However, above this temperature (ca. 14.0 ºC) a dramatic removal starts to occur. It is also noticed that, above the temperature at which a dramatic increase in removal is observed, the lower the number of treatments the more temperature-dependent is the percentage removal. For instance after one treatment, a removal of 6.4% and 40.1% is obtained at 16.3 ºC and 26.4 ºC, respectively, and after nine treatments the figures are 81.2% for 16.3 ºC and 95.6% for 26.4 ºC.

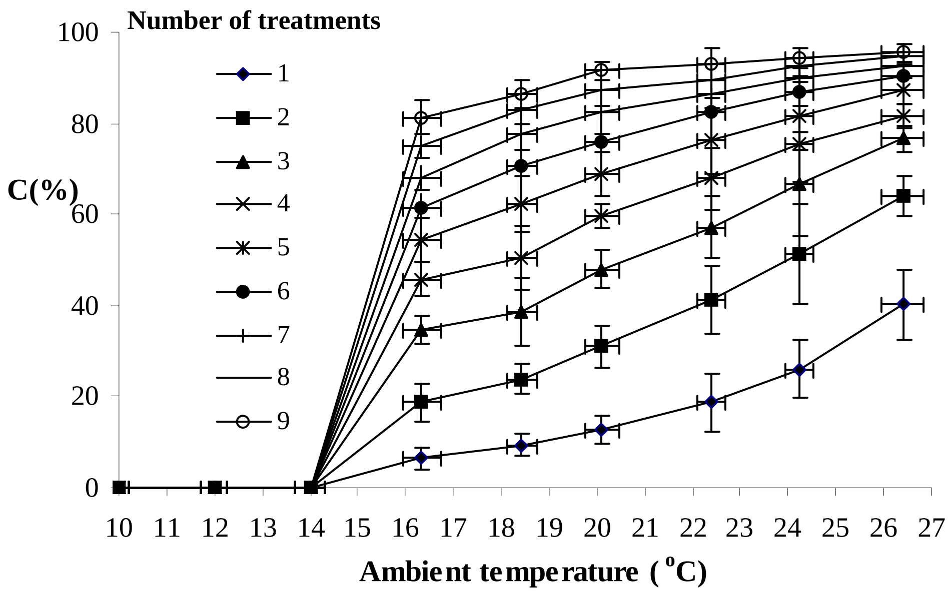

Figure 5.7: The percentage, C (%), of tarry oil removed from plumage of Little Penguin carcass as a function of the number of treatments, N. Vertical error bars represent the 95% confidence interval for five replicates. Horizontal error bars represent standard deviation for ambient temperature. The data are presented in Table 15 in Appendix 5.1. Individual profiles are documented from Tables 16 to 21 in Appendix 5.1.

The 3D presentation of removal as a function of the ambient temperature is presented in Fig. 5.8.

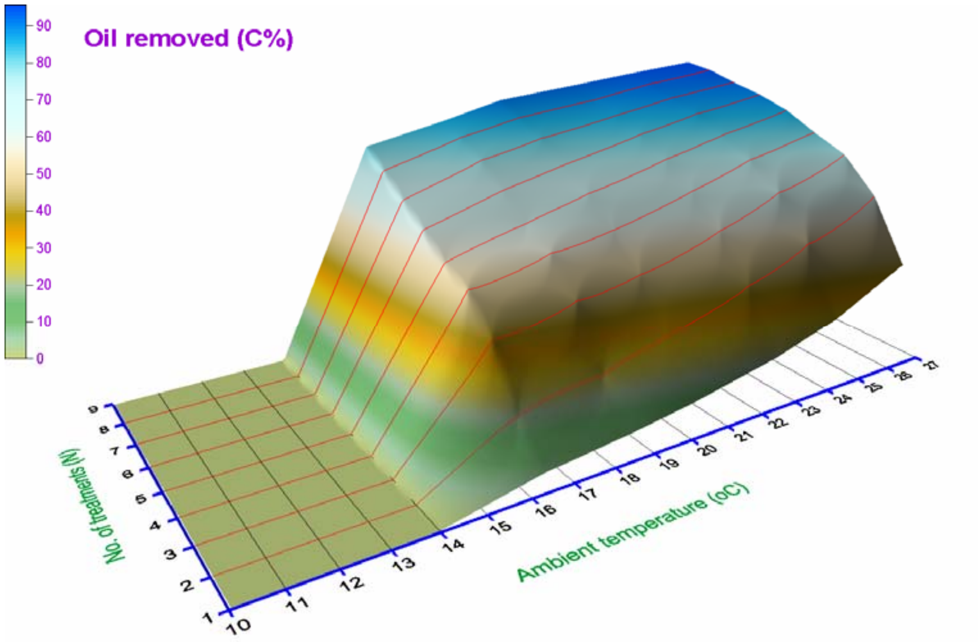

Figure 5.8: The 3D presentation of oil removal from penguin feather plumage (carcass) as a function of the ambient temperature.

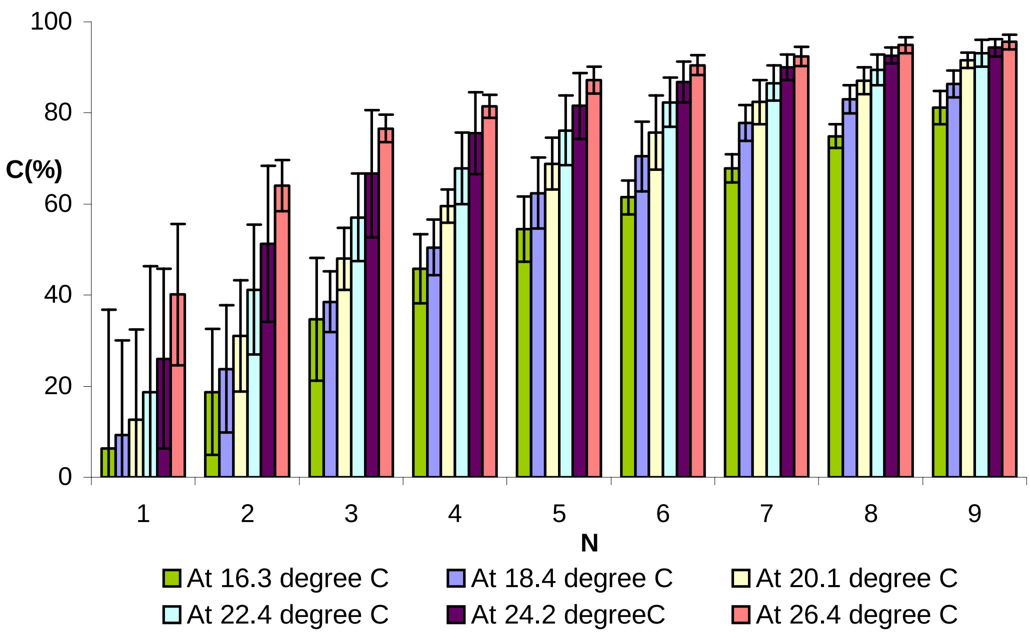

Figure 5.9: Histogram of the percentage, F (%), of tarry oil removed from penguin plumage as a function of the number of treatments, N, for the temperatures above the ‘acute’ temperature. Error bars represent the CV for five replicates. The data are presented in Table 22 in Appendix 5.1.

It was also observed that, the removal becomes much more reproducible as the number of treatments increases, as shown in Fig. 5.9. For example, the percentage uncertainties for these data, with respect to the CV (coefficient of variance), ranges from 15 - 30% for one treatment, 3 - 8% for five treatments and, notably, for the maximum number of treatments (9 treatments), where ca. 96% removal is effectively achieved, the experiments are highly reproducible, with the percentage uncertainty ranging from 1.7 - 3.6%.

The finding of temperature dependency of oil removal in this study is consistent with a number of studies, using different sorbents and substrates (Johnson *et al.*, 1973; Berkner *et al.*, 1977; Choi and Cloud, 1992; Aisien *et al.*, 2003; Haussard *et al.*, 2003; Sayed *et al.*, 2003; 2004; Urum *et al.*, 2004; 2005; Duong and Burford, 2006). In particular, the result of this study is very similar to a previous study by Toyoda *et al.* (2000), who used exfoliated graphite to remove very "heavy" oil (viscosity of 350 poise) from an aqueous medium. It was observed by the authors that no sorption is recorded for temperatures below 15 ^oC, however, above this temperature the sorption capacity increases dramatically and reaches a maximum capacity at a temperature of 30 ^oC.

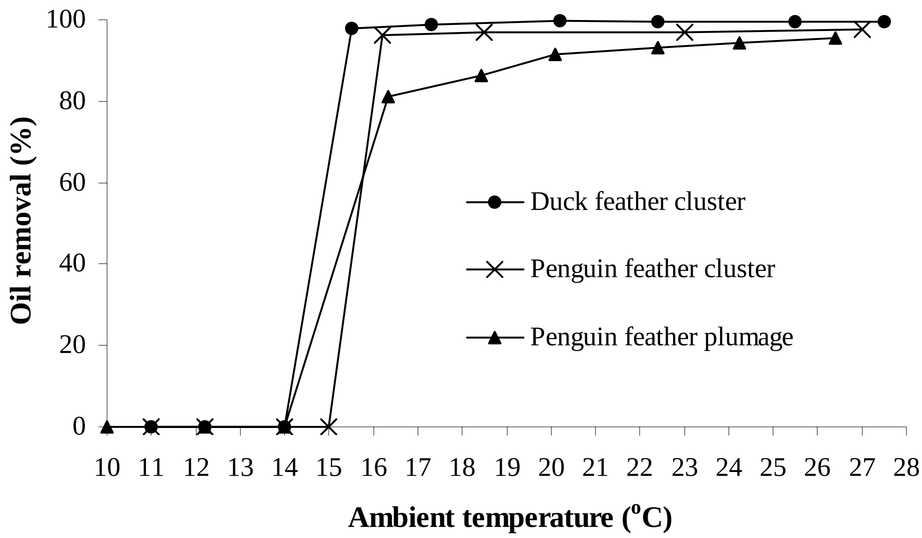

Figure 5.10: A comparison between the maximum removal for penguin feather plumage (nine treatments) with duck and penguin feather clusters (ten and fourteen treatments respectively) as a function of the ambient temperature. Error bars are omitted for clarity. The data are presented in Table 23 in Appendix 5.1.

A comparison between the maximum removal from penguin feather plumage (nine treatments) with the maximum removal from duck and penguin feather clusters (ten and fourteen treatments respectively) as a function of the ambient temperature was also conducted, and the results of this are shown in Fig. 5.10.

As can be seen from Fig. 5.10, although temperature dependency is found for the plumage it is not quite as acute as that for the clusters of feathers. This is probably due to the fact that the individual feathers of feather clusters are more accessible than those of plumage. Also, the maximum percentage removals are significantly different at the 95% confidence level.

5.4 Thermodynamic considerations of the temperature dependent removal of tarry oil

5.4.1 Experiments regarding the thermodynamics of the oil ab(d)sorption process

In order to explain the acute temperature dependency phenomenon, *vide supra*, and given that the experimental procedure allows an estimate of the equilibrium constant for the exchange of oil between the two surfaces (to be discussed later), it was decided to explore the overall thermodynamics of the process.

Initially, two simple experiments have been conducted to obtain preliminary thermodynamic information on the oil ab(d)sorption process.

An amount of engine oil (i.e. 10 g) was placed in a 100 mL beaker and its temperature was determined to be 21.9 ºC, using a normal laboratory thermometer. An amount of iron powder was added to the oil and the mixture was mixed by hand for 5 min to allow sorption to occur. The temperature of this mixture increased to 22.1 ºC indicating that the process of oil sorption on the magnetic particles was exothermic. A similar experiment was also conducted on another type of contaminant, Arab medium oil (AO) (lower in viscosity) and a similar outcome was achieved.

5.4.2 Thermodynamic considerations of the tarry oil removal process

The transfer of oil from the surface of the tarry residue onto the iron particles represents competitive adsorption between two different surfaces. The removal of the oil from the tarry surface (desorption) is expected to be endothermic, since the reverse process is expected to occur as a result of van der Waals forces (physisorption) - and such processes are typically exothermic (McCash, 2001). Thus:

$$\text{Oil (tar)} \rightleftharpoons \text{Oil (removed from tar)} \qquad \Delta H_1 > 0 \qquad (5.1)$$

The adsorption of the oil onto the surface of the iron is also assumed to be physisorption and hence this process is expected to be exothermic, *vide supra*, Section 5.4.1 . Thus:

$$\text{Oil (removed from tar)} \rightleftharpoons \text{Oil (onto Fe)} \qquad \Delta H_2 < 0 \qquad (5.2)$$

Overall, the removal of oil from the surface of the tarry deposit onto the iron particles is represented by:

$$\text{Oil (tar)} \rightleftharpoons \text{Oil (onto Fe)} \qquad (5.3)$$

For which (by Hess's Law):

$$\Delta H = \Delta H_1 + \Delta H_2 \qquad (5.4)$$

The overall enthalpy change, ΔH, for the oil removal process is therefore dependent on the relative magnitudes of the component enthalpy changes. If the desorption (endothermic process) has a greater magnitude than the sorption (exothermic process) then the overall reaction will be endothermic and *vice-versa.*

Assuming that the composition of the oil (mixture) removed from the surface of the tarry deposit onto the iron particles is the same as that in the bulk, the equilibrium constant for the overall process for each temperature and treatment status may be estimated as follows:

$$K = \text{Oil (on Fe)}/\text{Oil (on tar)} = P/(100 - P) \qquad (5.5)$$

where P is the percentage by weight of oil removed (%)[1].

[1] The mass-based equilibrium constant, K_{mass}, is only equal to the mole-based equilibrium constant, K_{mole} when the composition of the removed mixture is the same as the bulk. A sample calculation that demonstrated this principle is given in Appendix 5.2.

Therefore, the van't Hoff equation (5.6) can be employed to investigate the thermodynamics:

$$\ln K = -\Delta H°/RT + \Delta S°/R \qquad (5.6)$$

Where, $\Delta H°$ = enthalpy (J mol^{-1}), R = gas constant (8.314 J mol^{-1} K^{-1}), T = thermodynamic temperature (K), and $\Delta S°$ = entropy (J mol^{-1} K^{-1}).

It is found that by plotting lnK versus 1/T for data such as that represented in Fig. 5.8 (i.e. for each of the curves), good straight lines are obtained, Fig. 5.11. The remaining 32 such plots for duck and penguin feather cluster and feather plumage are shown in Appendix 5.1.

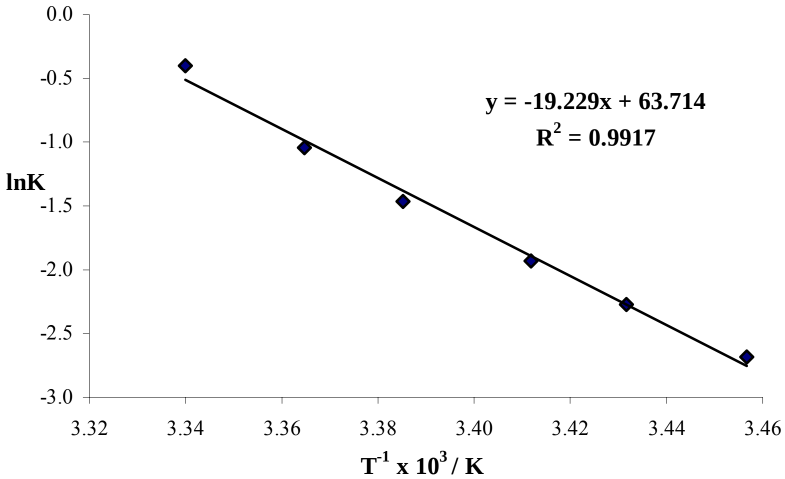

Figure 5.11: Representative van't Hoff plot for the sorption of tarry oil from feather plumage (N = 1 of Fig. 5.8).

The enthalpy and entropy of each treatment can be easily calculated from this above plot, in which the slope of the plot is $-\Delta H°/R$ and the intercept of the plot is $\Delta S°/R$. The standard error (SE) of the gradient ($-\Delta H°/R$) and intercept ($\Delta S°/R$) is calculated according to Kirkup (1994). The Gibbs free energy, $\Delta G°$, can be calculated by using the equation (Smith, 2004):

$$\Delta G° = \Delta H° - T\,\Delta S° \qquad (5.7)$$

5.4.3 Thermodynamic results

The calculations described below assume the composition of the oil that is removed and adsorbed onto the surface of the iron particles in each treatment is the same as the composition of the bulk. This is almost certainly not the case and, in fact, the composition of the oil removed might be expected to differ from that of the bulk in a unique way for every treatment and at each temperature. However, the composition of the oil removed would certainly be expected to be *reflective* of the composition of the bulk - and the approximation is obviously good enough to allow the van't Hoff equation to be successfully applied. The linearity of the plots supports this assumption. Furthermore, the data allow the following important deductions to be made.

For all experiments conducted for each feather type, the calculated ranges of values and averages for ΔH° and ΔS° for the removal of tarry oil from duck feather clusters, penguin feather clusters and penguin feather plumage, are given in Table 5.1. The detailed data for each individual treatment are given in Table 24 in Appendix 5.1.

Table 5.1: Estimated thermodynamic parameters for the magnetic harvesting process performed on duck feather clusters, penguin feather clusters and penguin feather plumage. Errors are represented by SE (Kirkup, 1994). The numbers of observations for duck feather clusters, penguin feather clusters and penguin feather plumage are 10, 14 and 9 respectively.

Feather type	ΔS°/J mol^{-1} K^{-1}	ΔH°/kJ mol^{-1}
Duck feather clusters	320.3 - 548.0 Mean: 501.9 ± 32.7	82.1 - 161.5 Mean: 139.9 ± 10.5
Penguin feather clusters	132.7 - 608.0 Mean: 284.3 ± 37.1	30.5 – 181.0 Mean: 77.9 ± 11.7
Penguin feather plumage	408.3 - 529.8 Mean: 437.5 ± 16.6	115.4 - 159.9 Mean: 126.9 ± 5.6

5.4.3.1 Enthalpy

The van't Hoff plots (Fig. 5.1 and Figs. 1 to 33 in Appendix 5.1) show that the enthalpy, ΔH°, is positive for all treatments for both feather clusters (duck and penguin) and feather plumage. Therefore, this process is highly *endothermic* and is consistent with the notion that raising the temperature will drive the process represented by Equation 5.3 to the right hand side – i.e. transferring more oil onto the iron particles. Since the overall process is endothermic, it follows that the magnitude of ΔH_1 must be greater than that of ΔH_2. This suggests that the van der Waals forces involved in the interaction of the oil molecules with the tarry surface are stronger than those involved with their interaction with the surface of the iron. This is not unexpected since the surface of the iron is likely to possess some hydrophilic character. In addition, the surface of the iron is expected to be more irregular than that of the tar, reducing the possibility of van der Waal's forces taking effect. The finding that the process is endothermic is consistent with a number of previous studies using magnetic particles in the sorption of heavy metal irons from an aqueous medium (Tamura *et al.*, 1983; Kim and Lee, 2001; Karasyova *et al.*, 2005).

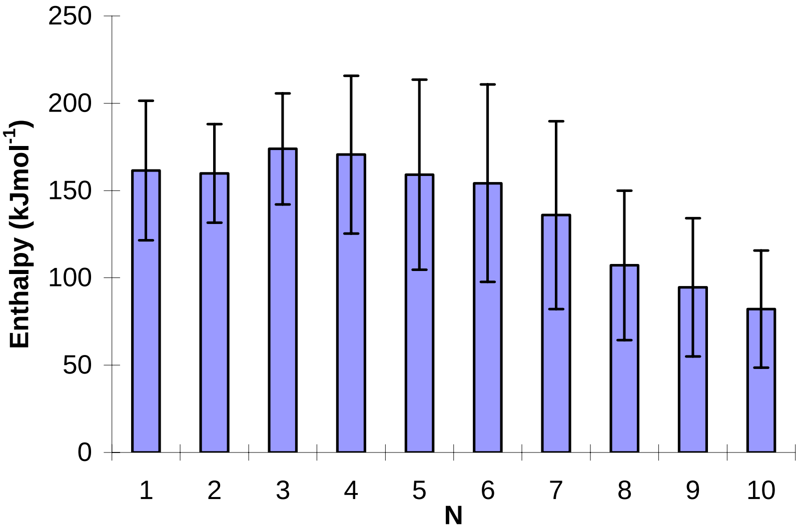

Figure 5.12: Enthalpy of the process of magnetic removal of tarry oil from duck feather cluster versus the number of treatments, N. Error bars represent SE where the SE of the gradient is calculated according to Kirkup (1994). The data are presented in Table 25 in Appendix 5.1.

On detailed examination of the data, Figs. 5.12 – 5.14, it may be observed that, for penguin feather clusters $\Delta H°$ tends to be higher for lower values of N. This trend also appears to be apparent for duck feather clusters and feather plumage, although the experimental error does not allow such a definitive statement to be made in these cases. For example, for duck feather clusters $\Delta H°$ ranges from 82.1 - 173.9 kJ mol^{-1}, Fig. 5.12. These values range from 30.5 - 181 kJ mol^{-1} for penguin feather clusters, Fig. 5.13, and 115.4 - 159.9 kJ mol^{-1} for feather plumage, Fig. 5.14, respectively. This suggests that the heat that must be provided decreases as the number of treatments increases since the amount of oil left to be removed decreases. It is also worth noting from Figs. 5.12 - 5.14 that the error bars of the enthalpy values of feather clusters, especially duck feather clusters are higher compared to those of penguin plumage. This could be explained by referring to their van't Hoff plots in Appendix 5.1, which indicate the lower correlation (R^2) for the plots of feather clusters (Figs. 1 - 24) than for those of the plumage (Figs. 25 - 33).

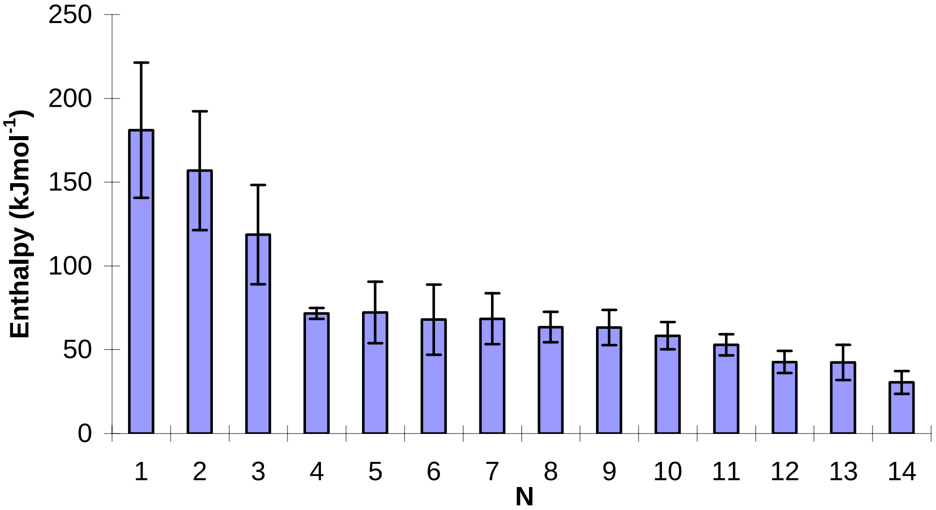

Figure 5.13: Enthalpy of the process of magnetic removal of tarry oil from penguin feather cluster versus the number of treatments, N. Error bars represent SE. The data are presented in Table 26 in Appendix 5.1.

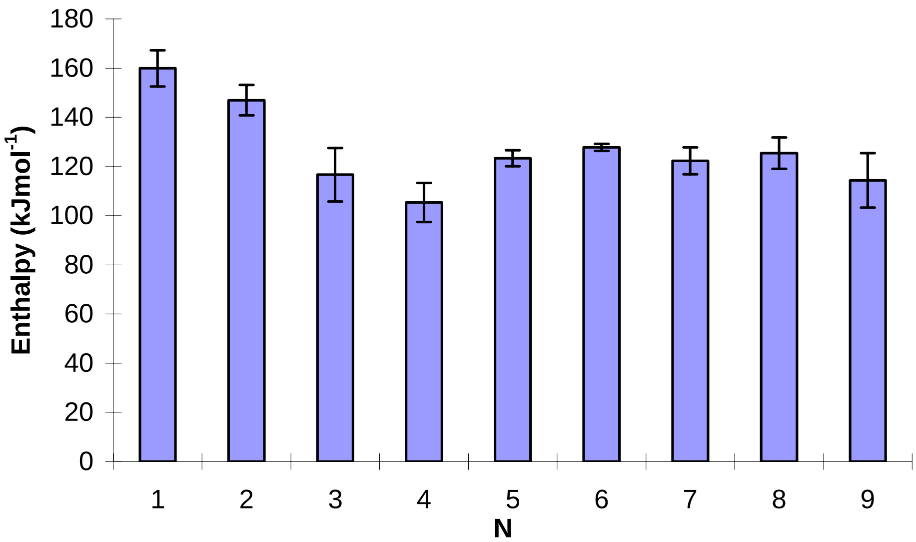

Figure 5.14: Enthalpy of the process of magnetic removal of tarry oil from penguin feather plumage versus the number of treatments, N. Error bars represent SE. The data are presented in Table 27 in Appendix 5.1.

5.4.3.2 Entropy

The van't Hoff plots (Fig. 5.1 and Figs. 1 - 33 in Appendix 5.1) show that the entropy, $\Delta S°$, is positive for all treatments for both feather clusters (duck and penguin) and feather plumage, indicating that this process is highly *entropy driven*. In term of the positive entropy change, it is also entirely expected that the oil components adsorbed onto the (expected) irregular surface of the iron will be more conformationally disordered than when adsorbed onto the relatively smooth surface of the tarry residue.

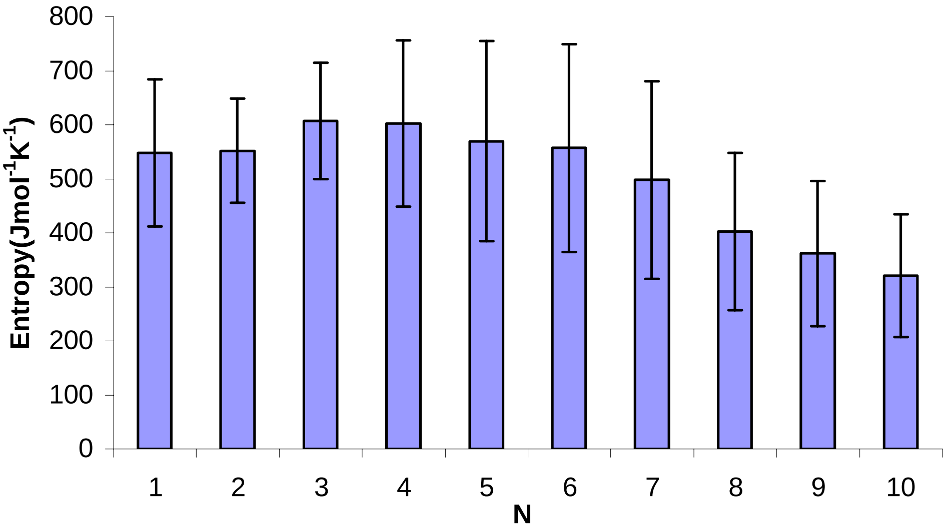

Figure 5.15: Entropy of the process of magnetic removal of tarry oil from duck feather cluster versus the number of treatments, N. Error bars represent SE. The data are presented in Table 25 in Appendix 5.1.

On detailed examination of the data, Figs. 5.15 – 5.17, it may be observed that, for penguin feather clusters $\Delta S°$ tends to decrease with increasing the number of treatments, N. This indicates that the magnitude of disorder decreases when the number of treatments increases. This trend is also found for duck feather clusters and feather plumage, although considerably less pronounced. For instance, for duck feather clusters $\Delta S°$ ranges from 320.4 - 548.0 J mol^{-1} K^{-1}, Fig. 5.15. These values range from 132.7 – 608.0 J mol^{-1} K^{-1} for penguin feather cluster, Fig. 5.16, and 408.3 - 529.8 J mol^{-1}K^{-1} for feather plumage, respectively, Fig. 5.17. It is also worth noting from Figs. 5.15 - 5.17 that the error bars of the entropy values of feather clusters, especially duck feather clusters are higher compared to those of penguin plumage. This could be explained by referring to their van't Hoff plots in Appendix 5.1, which indicate the lower correlation (R^2) for the plots of feather clusters (Figs. 1 - 24) than for those of the plumage (Figs. 25 - 33).

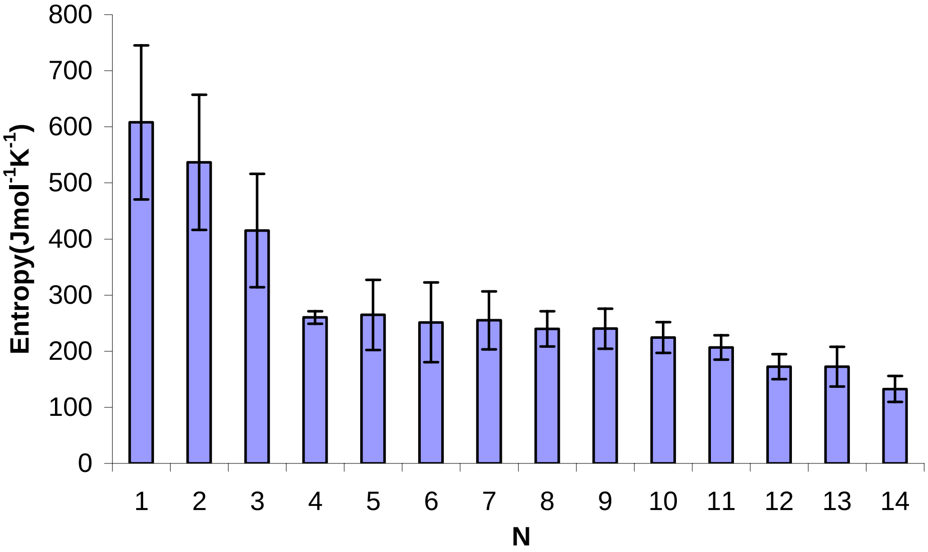

Figure 5.16: Entropy of the process of magnetic removal of tarry oil from penguin feather cluster versus the number of treatments, N. Error bars represent SE. The data are presented in Table 26 in Appendix 5.1.

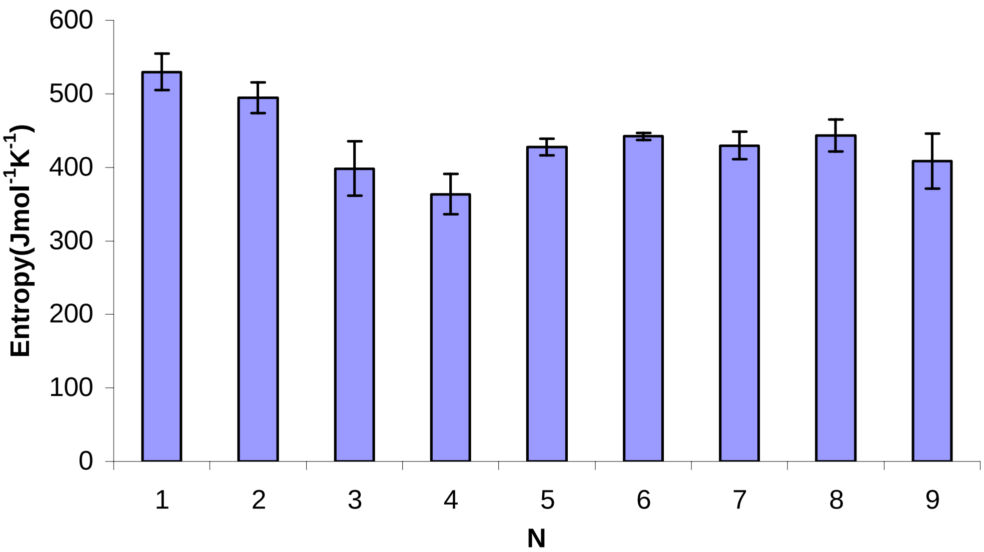

Figure 5.17: Entropy of the process of magnetic removal of tarry oil from penguin feather plumage versus the number of treatments, N. Error bars represent SE. The data are presented in Table 27 in Appendix 5.1.

5.4.3.3 Gibbs free energy

As would be anticipated, the Gibbs free energy, $\Delta G°$, is found to be negative for most of the treatments relating to duck feather clusters, Fig. 5.18. Similar outcomes are found for penguin feather clusters and penguin plumage; these plots are documented in Appendix 5.2. Negative $\Delta G°$ values suggest that the sorption is *spontaneous* and that the process (transfer to iron) is *thermodynamically favourable* overall (Sekar *et al.,* 2004). However, it is apparent that some of the $\Delta G°$ values at the early treatments (N = 1 – 2) are, in fact, positive. This is a result of the assumption that the composition of the removed oil is the same as that of the bulk, leading to K_{mass} deviating from K_{mole}, *vide supra.*

It is also worth noting that, in spite of the above assumption regarding K, the error values of $\Delta S°$ and $\Delta H°$ may be such that $\Delta G°$ can, in fact, be negative for the early treatments. For example, at N = 1 (Fig.5.1), $\Delta H°$ = 161.5 kJ mol^{-1} (Fig. 5.12), $\Delta S°$ = 548.0 J mol^{-1} K^{-1} (Fig. 5.15), temperature (T) = 288.5 K. Thus, $\Delta G°$, calculated according to Equation 5.7, will be (161.5 x 1000)-(288.5 x 548.0) = 3370 J mol^{-1} = 3.370 kJ mol^{-1} (Fig. 5.18). If the respective SE value of $\Delta S°$, which is 135.8 mol^{-1} K^{-1}, is added to the value of $\Delta S°$ in the calculation then $\Delta G°$ will become (161.5 x 1000)-(288.5 x (548.0 + 135.8)) = -35800 J mol^{-1} = - 35.8 kJ mol^{-1}, which is clearly negative.

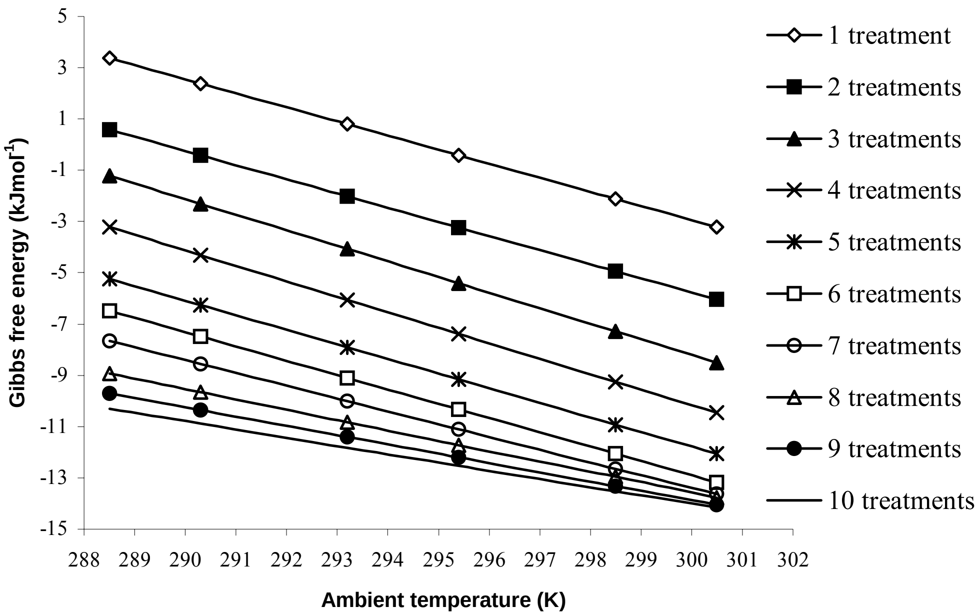

Figure 5.18: Gibbs free energy of the process of magnetic removal of tarry oil from duck feather clusters versus ambient temperature for all treatments. Error bars are omitted for clarity. The data are presented in Table 28 in Appendix 5.1.

It can be seen from Fig. 5.18 that the $\Delta G°$ becomes more negative with increasing temperature, indicating a greater driving force to adsorption onto the iron and subsequently leading to higher sorption capacity at higher temperatures (Kalavathy *et al.,* 2005), i.e. higher temperatures favouring the removal process (Singh *et al.,* 2005).

5.5 Conclusions

An investigation into the acute temperature dependency of the magnetic removal of tarry oil from feather clusters and plumage has been carried out. The thermodynamics of the process has been investigated in order to provide an insight into the phenomenon.

Experiments were conducted on the removal of tarry oil from feather clusters at different ambient temperatures. An acute temperature dependency for oil removal was observed. Specifically, below and at a certain temperature (ca. 14 ºC for duck feathers and ca. 15 ºC for penguin feathers) very little removal can be achieved, irrespective of the number of treatments. However, at temperatures above these, a dramatic removal starts to occur, achieving a maximum of 99.6% and 97.7% for duck feathers and penguin feathers, respectively. The temperature at which a dramatic increase in removal begins is found to be well below the pour point of the oil (ca. 28 ºC in this case). It was also noticed that above the acute temperature, the lower the number of treatments the more temperature-dependent is the percentage removal for both feather types. A comparison of the removal of tarry oil between duck and penguin feathers was also carried out, suggesting that the removal is higher for duck feathers than for penguin feathers.

Similar experiments with respect to the removal of the same tarry oil from the plumage of penguin carcasses were conducted. Not surprisingly, the acute temperature dependency observed for feather clusters was also observed in the case of plumage, but to a lesser extent. It was also worth noting that the maximum removal of 95.6% from plumage, after nine treatments, is quite encouraging given the fact that this is achieved without using any pre-conditioners. As with fresh contaminants, the removal is lower for plumage than for clusters of feathers.

These results are very encouraging with respect to the potential application of this technology to the treatment and rehabilitation of oiled wildlife, since they indicate that tarry contamination can be removed under conditions that are benign to birds. It is also important to emphasize that no pre-treatment (pre-conditioning) agents is required in either of the cases investigated. The contaminant was deliberately chosen to represent a worst-case scenario and it is likely that this phenomenon will also be observed for other forms of tarry contaminant.

An investigation into the thermodynamics of the magnetic process of tarry oil removal from both feather clusters (duck and penguin) and feather plumage was carried out. The resulting data have shown that $\Delta H°$ is positive for all treatments indicating that the magnetic tarry oil removal is *highly endothermic*. $\Delta H°$ is found to generally decrease when the number of treatments increases for penguin feather clusters, but to lesser extents for duck feather clusters and penguin feather plumage.

$\Delta S°$ is found to be positive for all treatments indicating that the magnetic tarry oil removal is *highly entropy driven*. This could be due to the oil components adsorbed onto the (expected) irregular surface of the iron being more conformationally disordered than when adsorbed onto the relatively smooth surface of the tarry residue. As with enthalpy, $\Delta S°$ appears to decrease with increasing the number of treatments for penguin feather clusters, but this is less pronounced for duck feather clusters and penguin feather plumage.

As expected, $\Delta G°$ is found to be negative for most of the treatments from duck and penguin feather clusters and feather plumage, suggesting that the sorption is *spontaneous* and that the process is *thermodynamically favourable* overall. It is also shown that the magnitude of $\Delta G°$ generally increases with increasing temperature, indicating a greater driving force to sorption, and subsequently leading to higher sorption capacity at higher temperatures (i.e. higher temperatures favour the removal process).

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CHAPTER 6: APPLICATION OF THE OPTIMAL GRADE OF MAGNETIC PARTICLES TO THE REMOVAL OF *WEATHERED* CONTAMINATION FROM FEATHERS

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CHAPTER 6: APPLICATION OF THE OPTIMAL GRADE OF MAGNETIC PARTICLES TO THE REMOVAL OF *WEATHERED* CONTAMINATION FROM FEATHERS

6.1 Introduction

When exposed to the environment, oil begins to weather (NOAA, 1997; Leighton, 2003). The phenomenon of weathering has been investigated for a long time since it presents a challenge to environmental remediation and wildlife rehabilitation and, in this regard, some models or patterns of weathering have been developed (Daling and Strom, 1999; Michel and Hayes, 1999; Prince *et al.*, 2002; AMSA, 2004). Technically, weathering of oil is defined as the process of spilled oil changing in its chemical composition and physical properties and, on average, this process can take up to a year to complete (Leighton, 2003). According to ITOPF-a (2004), there are eight major processes in the weathering of oil spills, namely: spreading, evaporation, dispersion, emulsification, dissolution, oxidation and sedimentation. These processes are represented in Fig. 6.1.

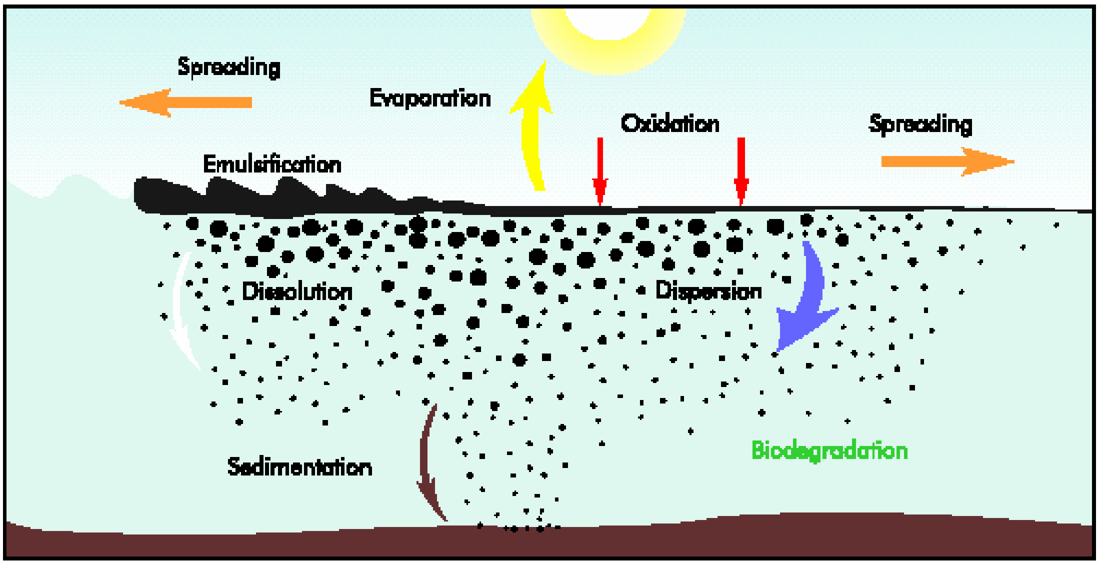

Figure 6.1: Processes of weathering (ITOPF- a, 2004).

In general, at the early stage of the weathering process, spreading, evaporation, dispersion, emulsification and dissolution play a more important role. However, later in the process, oxidation, sedimentation and biodegradation dominate, determining the ultimate fate of the oil (ITOPF-b, 2004). When oil is weathered it usually forms sticky substances such as tar balls or asphalt, and this makes the cleaning process harder (USEPA, 2004). The common method to date to remove weathered contamination from subsurface beach materials is the use of high pressure, hot water flushing and even hand-cleaning for some severely oiled rocks (Tumeo *et al*., 1994). This can also include nutrient addition to accelerate bioremediation of the weathered contamination (Michel and Hayes, 1999). Biochemical agents can also be used to remediate weathered oil. For example, a bio-surfactant (PES 51) was used in the cleaning of weathered contamination on LaTouche Island after the *Exxon Valdez* oil spill (Tumeo *et al.*, 1994). In some cases, surface washing agents are used with a view to softening the weathered oil and enhancing flushing steps (NOAA, 2001).

Weathering is of particular concern for oil on the fur or feathers of wildlife (OWCN, 1999, 2003; Bryndza, 2005). This is not an uncommon scenario, since it may take days or even weeks for affected animals to be discovered and collected by rescuers. For example, following the *Sea Empress* oil spill on 15 February 1996 off the coast of South West Wales (UK), the first oiled birds came ashore on 17 February and the last ones were collected on 8 March 1996 (Clark *et al.*, 1997). A recent oil spill in Ventura County, California (USA) is believed to have killed or injured around 3000-5000 seabirds, some of which were coated with heavily weathered /tarry oil (Mecoy, 2005).

To date, there have been only a limited number of references to the removal of weathered/tarry contamination from feathers or fur (Bryndza *et al.*, 1991; Holcomb and Russell, 1999; Hill, 1999; OWCN, 1999, 2003; Monfils *et al*., 2000; USFWS, 2002; Walraven, 1992, 2004; IBRRC, 2000; TSBRR, 2005). Usually, the common technique for the removal of weathered/tarry contamination from feathers involves the use of detergents and a large amount of warm water, together with pre-treatment (conditioning) agents (OWCN, 1999). Although these conventional techniques have acquired some degree of success, they are time-consuming and labour-intensive. Also, the pre-conditioning agents themselves need to be removed during the cleaning process (Frink and Crozer-Jones, 1986; USFWS, 2002). Therefore, the treatment of birds coated with weathered/tarry contamination can be problematic (Holcomb and Russell, 1999; Bryndza, 2005), representing a considerable research challenge.

In Chapter 4, the optimal iron powder (i.e. the superfine spongy annealed grade), has been shown to be effective in removing up to ca. 100% of various fresh (non weathered/tarry) contaminants from different substrates, including feathers. This grade has also been investigated for the removal of non-weathered tarry oil from feathers, as reported in Chapter 5. This chapter describes an investigation into the removal from duck and penguin feathers of various contaminants that have been allowed to weather over time, employing the optimal particles. The role of a pre-conditioner, in this case olive oil, has also been investigated.

6.2 Removal of weathered oil from feather clusters

6.2.1 Monitoring the weight loss of weathered oiled feathers over time

For the purpose of these experiments weathering is considered to be the extent of evaporation of the more volatile fractions over time. In this regard, evaporation is considered to be the major process of weathering (Mullin and Champ, 2003), resulting in around 5-10% of oil weight lost for heavy crude, and 20-60% for lighter crude oil spills (NOAA, 1997). Also, for wildlife contamination, it is not necessary for long-term, non-evaporative weathering processes to be considered since this would extend beyond the survival time of the animal. A similar procedure on the mimicking of oil weathering has been documented (Urum *et al.*, 2004; 2005).

The contaminants used in these experiments are Shell crude oil (SO) and bunker oil (BO2) (see Table 2.2 in Chapter 2). SO is tarry and semi-solid oil at room temperature with a viscosity between 3000 to 4000 cSt at 100 ºC. Therefore, it is considered to be appropriate to represent a “worst case scenario” of tarry contamination in nature. BO2 is a highly viscous oil (222 cSt at 40 ºC), and is sometimes found as a contaminant at the Phillip Island Nature Park, posing threats to the resident little penguins (Jessop, *Personal communication*). The feathers used in these experiments are clusters of breast/contour feathers from the Mallard Duck (*Anas platyrhynchos*).

In this study, the weathering process of oil was simulated and conducted in the laboratory as follows: a cluster of feathers was immersed in a melt of the oil that was then allowed to solidify to a tarry deposit. The resultant tarry feathers were left to hang in the air at room temperature for up to fourteen-days. The weight of the oiled feathers was monitored over time and this was taken to be a measure of the degree of weathering. It may be seen in Fig. 6.2 that, for crude oil (SO), the evaporation rate is fairly high for the first five days, resulting in around 14% weight loss. However, after seven-days the evaporation rate slows considerably and at this stage the oil is considered as having been weathered significantly (representing around 16% weight loss). After fourteen days of weathering, subsequent oil loss is very small and the oil is considered to be almost fully weathered (representing around 19% weight loss). For bunker oil (BO2), fourteen days of weathering results in around 14% weight loss, Fig. 6.2.

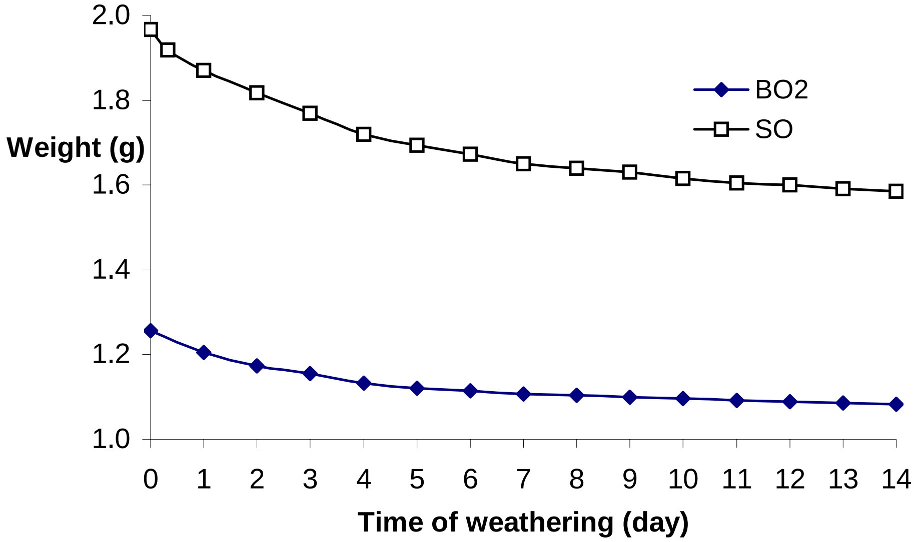

Figure 6.2: Weight versus time of weathering for oiled duck feather clusters. The data are presented in Table 1 in Appendix 6.

6.2.2 Removal of weathered crude oil

6.2.2.1 Comparison of oil removal for different times of weathering

The weathering process has been reported to affect the dispersion of oil in water (Moles *et al.*, 2002) and especially the removal of oil from feathers (Bassères *et al.*, 1994; Monfils *et al.*, 2000). As demonstrated in Fig. 6.2, the oil becomes significantly weathered after seven days of weathering and almost fully weathered after fourteen days. Since the extent of weathering may affect the efficacy of magnetic cleansing, controlled experiments were conducted on the magnetic removal of tarry oil that had been allowed to weather for one, seven and fourteen days.

In these experiments, a bottle containing crude oil (SO) was placed in a warm water bath to melt the oil. The flowing liquid oil was poured into a beaker. A number of clusters of feathers were weighed prior to being dipped in the contaminant. These oiled clusters were then left to weather at room temperature for one, seven and fourteen days. The oiled feathers were weighed before being covered with magnetic particles and subsequently cleansed magnetically using a magnetic tester. The methodology for calculating the percentage removal of weathered oil from feather clusters was similar to that for the fresh oil experiments mentioned in the previous chapters. All experiments were conducted in five-fold replicate at a temperature of ca. 295 K, being above the acute temperature required for removal to occur (Orbell *et al.*, 2005). The results enable the comparison of oil removal for both duck and penguin feathers after different times of weathering, and are presented in Fig. 6.3 and Fig. 6.4 respectively.

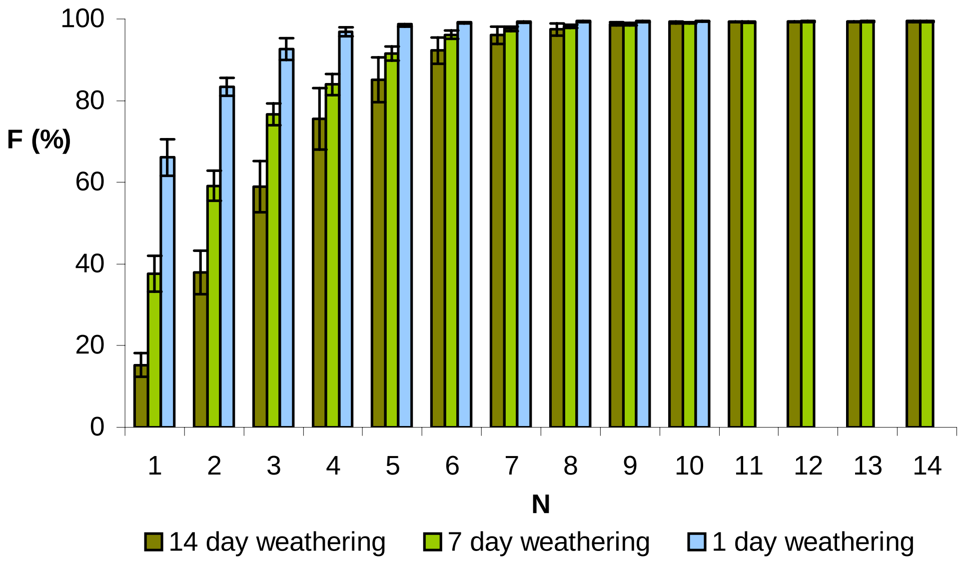

Figure 6.3: Comparison amongst different times of weathering for the removal of crude oil from duck feathers, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 2 in Appendix 6. The individual profiles corresponding to each time of weathering are presented in Tables 3 to 5 in Appendix 6.

As can be seen in Fig. 6.3, the pick-up of oil from duck feathers, particularly for the first four treatments, decreases as the time of weathering increases. This is consistent with a previous study suggesting that oil removal becomes lower when time of weathering increases (Bassères *et al.*, 1994). Thus the initial removal is 66.1% for one day of weathering, which is significantly higher than the 37.7% for seven days and higher again than the 15.3% for fourteen days. This is probably due to the fact that lighter fractions, that are more abundant earlier on in the weathering process, are more susceptible to cleaning. However, the difference in the removal at different times of weathering becomes less pronounced as the number of treatments increases. Thus the maximum removal is comparable irrespective of the time of weathering, showing a removal greater than 99.3% in all cases. It is noted, however, that the number of treatments needed to achieve maximum removal is less for a shorter time of weathering, being N = 10 for one-day weathering compared to N = 14 for both seven-day and fourteen-day weathering. This is similar to a previous study that suggests that the longer the time of weathering, the greater the cleaning time of weathered oil from feathers (Monfils *et al.*, 2000).

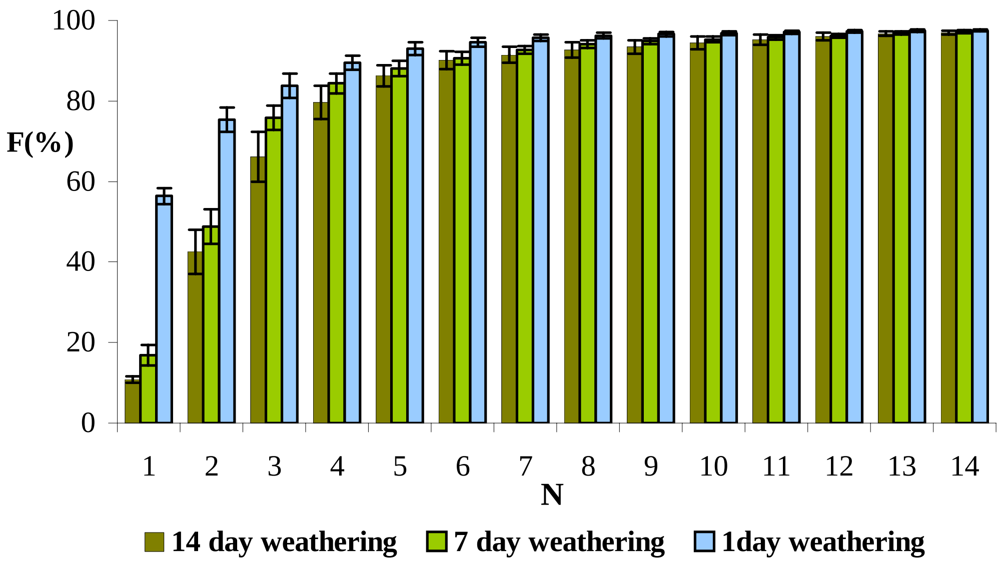

Figure 6.4: Comparison amongst different times of weathering for the removal of crude oil from penguin feathers, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 6 in Appendix 6. The individual profiles for each time of weathering are presented in Tables 7 to 9 in Appendix 6.

As with duck feather clusters, the pick-up of oil from penguin feathers, particularly for the first three treatments, decreases as the time of weathering increases. For the initial treatment, the removal is 56.4% for one day weathering, 16.9% for the seven days and 10.8% for fourteen days weathering. However, the difference in oil removal for different times of weathering becomes less pronounced as the number of treatments increases.

Thus, there is little difference in the maximum removal for all times of weathering, being 97.5%; 97.2% and 97% for the one-day, seven-day and fourteen-day weathering, respectively.

6.2.2.2 Comparison of oil removal for different feather types

A comparison of the removal of seven-day weathered crude oil (SO) between duck and penguin feathers is shown in Fig. 6.5. As can be seen overall the removal of oil is higher for duck feathers than for penguin feathers. This indicates that duck feathers are significantly more responsive to treatment than penguin feathers *for this kind of contaminant*. For example, the initial removal for duck feathers is 37.6%, much higher than 16.9% for penguin feathers. However, the difference in oil removal between duck and penguin feathers becomes less pronounced as the number of treatments increases. Consequently, the maximum removals are more comparable, higher for duck feathers than for penguin feathers, at 99.4% and 97.2%, respectively.

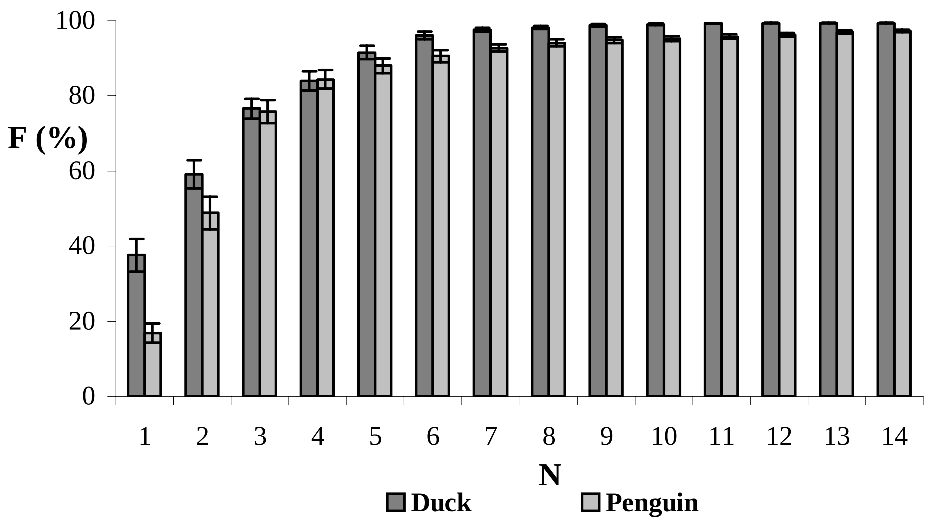

Figure 6.5: Comparison between duck and penguin feathers for the removal of seven-day weathered crude oil, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 11 in Appendix 6.

Similar outcomes to the above are observed for one-day and fourteen-day weathered crude oil removal from duck and penguin feathers. These data are presented in Table 10 and Table 12, respectively in Appendix 6.

6.2.3 Removal of weathered bunker oil

6.2.3.1 Comparison of oil removal for different times of weathering

Similarly, experiments have been conducted to remove bunker oil (BO2) that has been allowed to weather for one day, seven days and for fourteen days, from feathers. The methodology to carry out these experiments was similar to what was presented in the previous section for crude oil. However, it is noted that since the oil is a flowing liquid, it is not required to melt down before doing experiments. The oil removals from duck and penguin feather for different times of weathering (one day, seven days and fourteen days) are presented in Fig. 6.6 and Fig. 6.7.

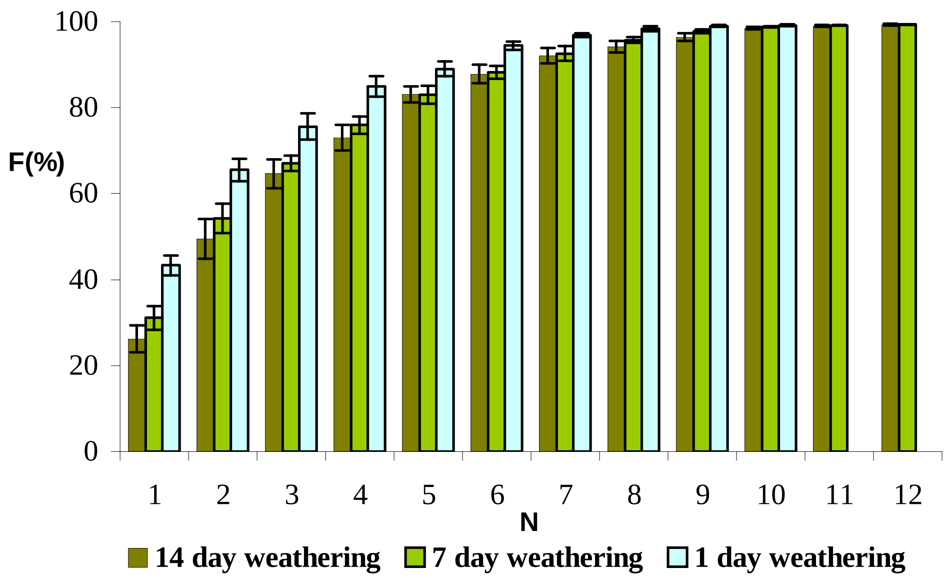

Figure 6.6: Comparison amongst different times of weathering for the removal of bunker oil from duck feathers, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 13 in Appendix 6. The individual profiles for each time of weathering are presented in Tables 14 to 16 in Appendix 6.

As shown in Fig. 6.6, the removal of oil from duck feathers, especially for the first several treatments, generally decreases as the time of weathering increases. The initial removal is 43.3% for one-day weathering, considerably higher than 31.1% for seven-day weathering and 26.2% for fourteen-day weathering. However, the difference in oil removal between times of weathering becomes less pronounced as the number of treatments increases. Thus, the maximum removal is more comparable, exceeding 99.2% for all times of weathering.

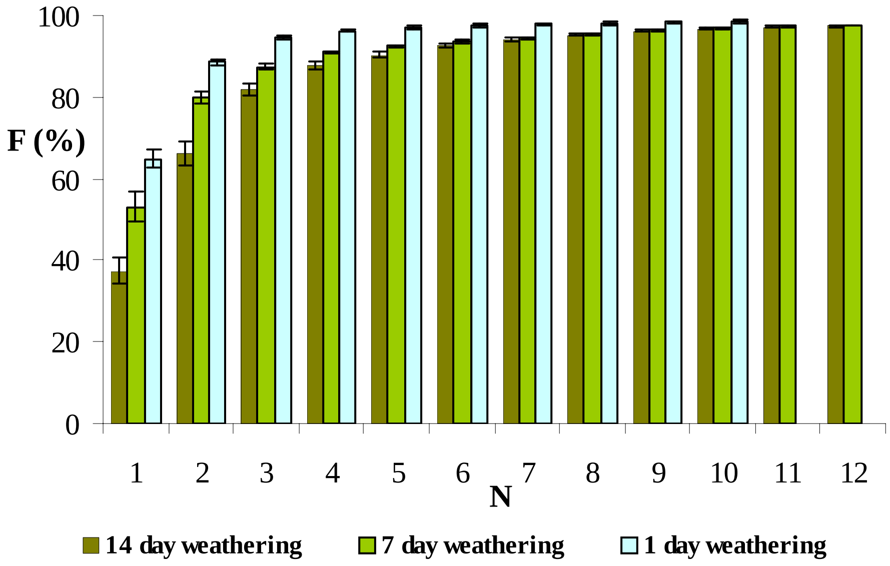

Figure 6.7: Comparison amongst different times of weathering for the removal of bunker oil from penguin feathers, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 17 in Appendix 6. The individual profiles for each time of weathering are presented in Tables 18 to 20 in Appendix 6.

As with duck feather clusters, the pick-up of oil from penguin feathers, especially for the first four treatments, decreases as the time of weathering increases, Fig. 6.7. Again, the initial removal is different amongst different times of weathering, at 64.9% for the one-day, significantly higher than 53.1% for the seven-day weathering, and 37.4% for the fourteen-day weathering. However, the difference in oil removal amongst the times of weathering becomes less pronounced as the number of treatments increases. Thus, there is little difference in the maximum removal, showing, in turn, 98.6%; 97.6% and 97.4% for the one, seven and fourteen days of weathering. It is also noted that the number of treatments needed to achieve maximum removals from both duck and penguin feathers is less for a shorter time of weathering, being N = 10 for one-day weathering compared to N = 12 for both seven-day and fourteen-day weathering.

6.2.3.2 Comparison of oil removal for different feather types

A comparison of the removal of seven-day weathered bunker oil (BO2) between duck and penguin feathers is shown in Fig. 6.8.

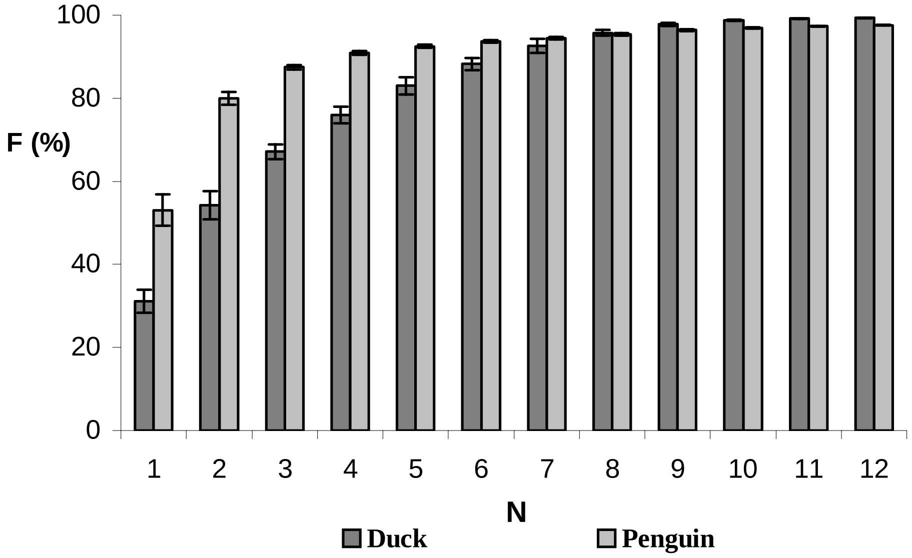

Figure 6.8: Comparison between duck and penguin feathers for the pick-up of seven-day weathered bunker oil, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 22 in Appendix 6.

It can be seen from Fig. 6.8 that, unlike crude oil (see Fig. 6.5), the removal of bunker oil, during the first 6 treatments, is significantly higher for penguin feathers than for duck feathers. This indicates that penguin feathers are more responsive to treatment in the initial stages than duck feathers *for this kind of contaminant*. For example, the initial removal is 53.1% for penguin feathers, significantly higher than 31.1% for duck feathers. However, as observed previously for crude oil, the difference in oil removal between duck and penguin feathers becomes less pronounced as the number of treatments increases and, in this case, the maximum removal becomes superior for duck feathers at 99.4% compared to penguin feathers at 97.6%.

Similar outcomes are observed for one and fourteen days of weathering. These data are presented in Table 21 and Table 23, respectively in Appendix 6.

6.2.4 Comparison of removal between weathered crude and bunker oil

Comparisons of the percentage contaminant removal from duck and penguin feathers between weathered crude oil (SO) and bunker oil (BO2) were made and the results are presented in this section.

6.2.4.1 Removal from duck feathers

For the removal of weathered contaminant (one, seven and fourteen days) from duck feathers, a comparison was made between crude oil and bunker oil. The results for seven-day weathering are shown in Fig. 6.9. The data for one-day and fourteen-day weathering are presented in Tables 25 & 26 in Appendix 6.

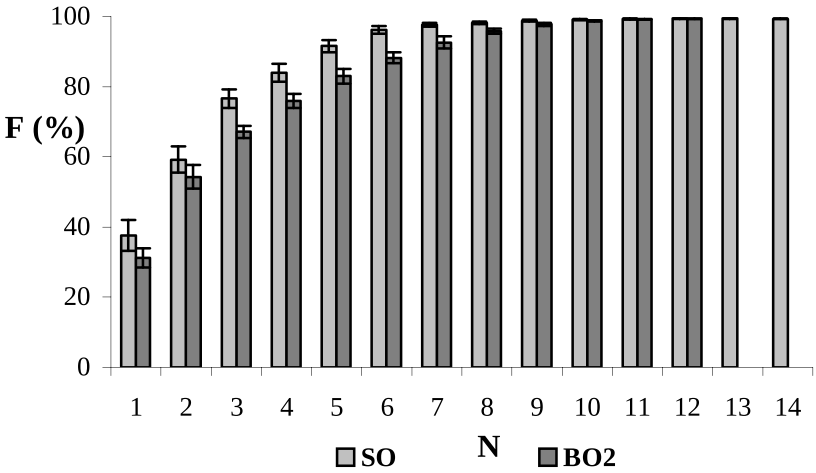

Figure 6.9: Comparison between crude oil and bunker oil for the removal of the seven-day weathered oil from duck feathers, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 24 in Appendix 6.

It was found that, for the one-day and seven-day times of weathering; the oil removal, especially for the first seven treatments, is generally higher for SO than for BO2. However, the opposite is found for fourteen-day weathering. For seven-day weathering the initial removal is 37.6% for SO, compared to 31.1% for BO2, Fig. 6.9. The respective figures for fourteen-day weathering are 15.3% and 26.2%. However, for all three times of weathering and for both types of oils, the maximum removal is ca. 99.4%.

6.2.4.2 Removal from penguin feathers

For the removal of weathered contaminant (one, seven and fourteen days) from penguin feathers, a comparison was made between crude oil and bunker oil. The results for seven-day weathering are shown in Fig. 6.10. The data for one day and fourteen-day weathering are presented in Tables 28 & 29 in Appendix 6.

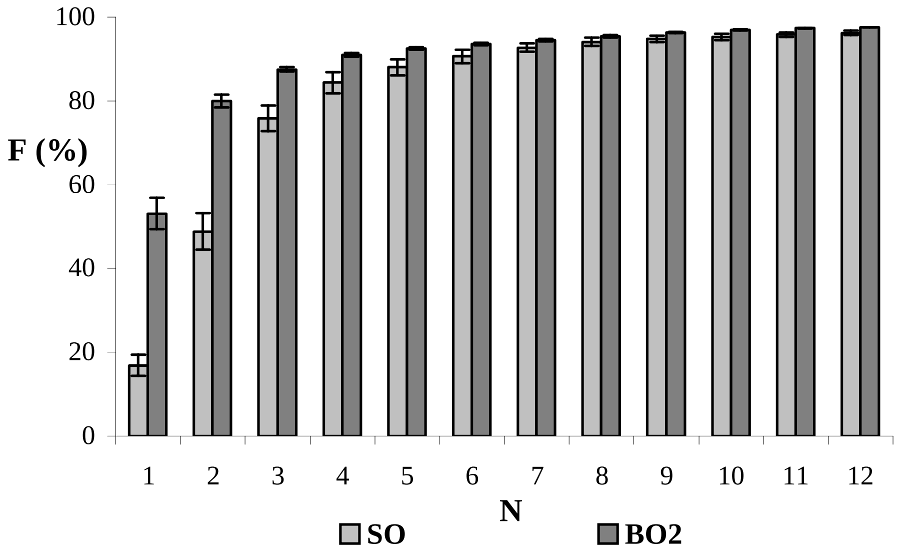

Figure 6.10: Comparison between crude oil and bunker oil for the removal of seven-day weathered oil from penguin feathers, F (%), as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are presented in Table 27 in Appendix 6.

It was found that for all times of weathering, the oil removal is lower for SO than for BO2. This is in contrast with the results for duck feathers. This is due to the fact that penguin feathers and duck feathers are different in their microstructures. For instance, for seven-day weathering the initial removal is 16.9% for SO compared to 53.1% for BO2, Fig. 6.10. For all times of weathering, the difference in removal becomes less pronounced as the number of treatments increases. Thus the maximum removal is slightly lower for SO than for BO2. For instance, the maximum removal of the seven-day weathered oil is 96.2% for SO, lower than 97.6% for BO2. These figures are different at the SE level.

6.2.5 Magnetic cleansing of weathered oil using olive oil as a pre-conditioner

6.2.5.1 Removal of olive oil

The use of pre-treatment (conditioning) agents is considered necessary in the cleaning of weathered contamination from feathers (USFWS, 2002; OWCN, 2003). Olive oil has been reportedly used as a pre-treatment agent in the removal of weathered oil from wildlife (William, 1985; Hill, 1999; OWCN, 1999; 2003). It has also been suggested as one of the most effective pre-conditioning agents in the magnetic cleaning of oiled feathers (Ngeh, 2002). However, pre-conditioning agents themselves also need to be removed during the cleaning process to prevent the problem of replacing an existing contaminant with a new one (Frink and Crozer-Jones, 1986; USFWS, 2002). Therefore, an investigation into the ad(b)sorption of olive oil from two matrices: glass (petri dish) and duck feathers, using the optimal iron powder grade, has been carried out. The methodology for the removal of olive oil from glass and feathers was analogous to that used for the other contaminants, discussed in Section 2.1.1 and Section 2.1.2. The results of the pick-up of olive oil from glass and duck feathers are shown in Figs. 6.11 and 6.12.

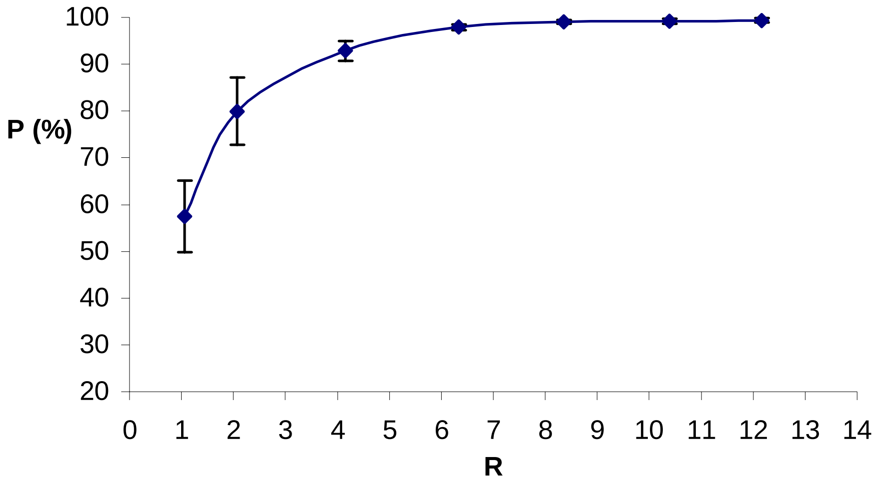

Figure 6.11: The pick-up of olive oil from glass, P (%), as a function of the particle-to-olive oil ratio, R. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 30 in Appendix 6.

It can be seen from Fig. 6.11 that olive oil is effectively removed from the glass by the magnetic particles. An initial pick-up of P = 57.5% is obtained at R = 1 and the maximum removal is P_o = 99.4% at a ratio of R_o = 12.

It also can be seen from Fig. 6.12 that the percentage removal of olive oil from the feathers is extremely high, ranging from 96.6% for the initial treatment to ca. 100% after only seven treatments.

From the results presented above, it is clearly indicated that the optimal grade of iron has a very high affinity for olive oil, showing a final removal of ca. 100% from glass and duck feathers. Therefore, olive oil is considered to be an appropriate pre-conditioning agent for the magnetic cleansing of weathered contamination.

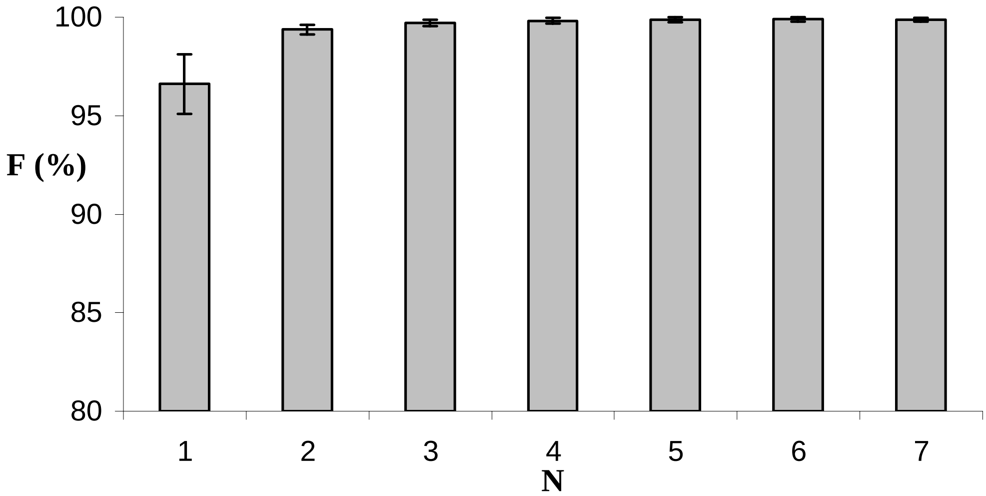

Figure 6.12: The removal of olive oil from duck feathers, F (%), as a function of the number of treatments, N, using the optimal magnetic particles. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 31 in Appendix 6.

6.2.5.2 Preliminary investigations on the use of olive oil in the cleansing process

Anecdotally, the use of pre-conditioners is generally considered to offer better results than without using pre-conditioner in the cleaning of oil from feathers. However, certain pre-conditioners may be more suitable for some contaminants than others (Bryndza, 2005; TSBRR, 2005). Moreover, the questions of when and how to apply pre-conditioners during the (magnetic) cleansing process can also be an important consideration (Dao *et al*., 2006). This section investigates the role of olive oil as a pre-conditioner in magnetic cleansing with respect to the removal of seven-day weathered crude oil from penguin feathers.

In preliminary experiments, it was previously reported (Ngeh, 2002) that olive oil applied at the outset of the magnetic harvesting process softens weathered oil on feathers and improves its removal. The process that was developed involves saturating the oiled feathers with olive oil and then proceeding with magnetic removal whilst re-applying the pre-conditioner every three treatments during the cleansing process. Using this method in the current study, a removal of 98.6% was achieved after 23 treatments, which is quite promising. However, this method is considered to be less than ideal since there is a relatively large amount of pre-conditioner that needs to be removed during the process leading to a large number of treatments being required before a satisfactory outcome is achieved. Therefore, the procedure was modified such that the olive oil is applied at the beginning of the harvesting process and then re-applied again every five treatments. This results in a removal of about 99% after around 25 treatments. However, these two methods of applying the olive oil, although offering promising removals, are quite time-consuming, needing up to 25 treatments to achieve maximum removal. Therefore, other protocols for the application of the pre-conditioner were explored.

As the experiments were conducted at a temperature of ca. 295 K (above the acute temperature) for the weathered crude oil (SO), the (essentially) solidified contaminant is still soft enough for removal to be initiated. The same situation was found for weathered bunker oil (BO2). It is also demonstrated in Section 6.2.3.1 that the overall removals of both weathered crude and bunker oils from feathers, without using any pre-conditioning agent, are quite high. Therefore, the use of pre-conditioner at the beginning of the cleansing process may not be necessary and could actually be problematic, especially for a contaminant like bunker oil (Healy, *personal communication*). Therefore, it was decided that olive oil be used only at a stage where the percentage of oil removal becomes nearly constant, at N = 10 treatments, and then be used only once more at N = 15. This approach results in an overall improvement of 99.1% after 20 treatments. However, the number of treatments is still very high.

It was found during the experiments in Section 6.2.3.1 that up to the first 5 or 6 treatments, the weathered oil could be easily removed (as can be seen in Fig. 6.3; Fig.6.4; Fig. 6.6; and Fig. 6.7). However, beyond this point, the removal becomes less efficient. Visually, the residual contaminant can be seen to remain on the feathers suggesting that the contaminant is more difficult to remove at this stage in the process compared with the earlier stages in the process. The application of olive oil at this stage in the process might thus be more appropriate. A subsequent trial of this approach where the olive oil is applied at N = 6 (after five treatments) and is then applied again at N = 10, results in a maximum removal of around 99.1% after only 14 treatments (for penguin feathers). The outcome of these experiments is shown in Fig. 6.13.

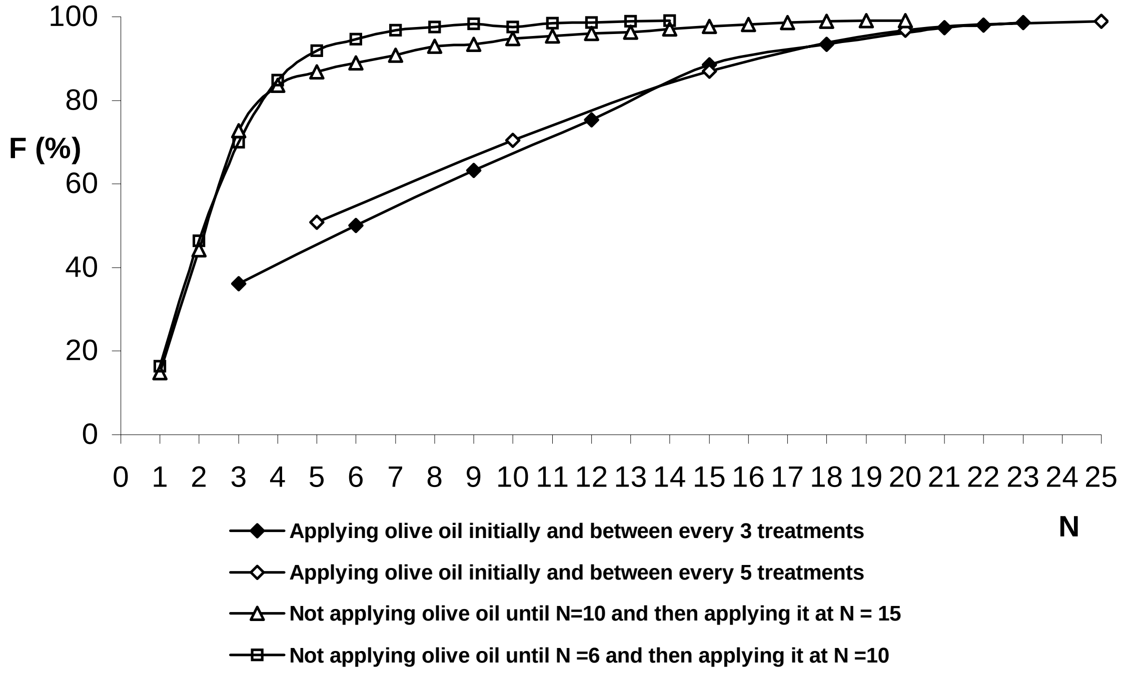

Figure 6.13: Comparison of the magnetic removal of seven-day weathered crude oil from penguin feathers, F (%), as a function of the number of treatments, N, for different ways of applying olive oil as a pre-conditioner. Experiments were conducted in three replicates. Error bars are omitted for clarity. The data are presented in Table 32 in Appendix 6. The individual profiles are presented in Table 33, Table 34, Table 35 and Table 36 in Appendix 6.

6.2.5.3 Detailed investigations into the use of olive oil

Having established that the effectiveness of applying a pre-conditioner in the magnetic cleansing process depends upon the point of application with respect to the number of treatments, further experiments were carried out to investigate the use of olive oil in the magnetic cleansing of weathered crude and bunker oils from both duck and penguin feathers. In all experiments, the optimal iron powder was employed. The methodology was analogous to that used for the removal of fresh oil.

Five feather clusters were coated with oil, and then left to weather for seven days (for crude oil) and fourteen days (for bunker oil) before treatment. Each feather cluster was subjected to five treatments, without using olive oil. It was then saturated with olive oil at N = 6 to soften the residual contaminant and was allowed to drain for 10 min. Olive oil was used subsequently only one more time at N = 10, if considered necessary. The oiled feathers were cleansed with iron powder until maximum removal was achieved. This occurred at N = 10 and N = 14 for duck and penguin feathers respectively.

It is also worth noting that for the following experiments, using olive oil as a pre-conditioner, seven-day weathering was selected for crude oil, whilst fourteen-days weathering was chosen for bunker oil. This is because crude oil is already a semi-solid whereas bunker oil, although very sticky, is a flowing liquid.

Crude oil: The results for the magnetic removal of seven-day weathered crude oil from duck and penguin feathers, using olive oil as a pre-conditioner, are presented in Fig. 6.14 and Fig. 6.15, respectively.

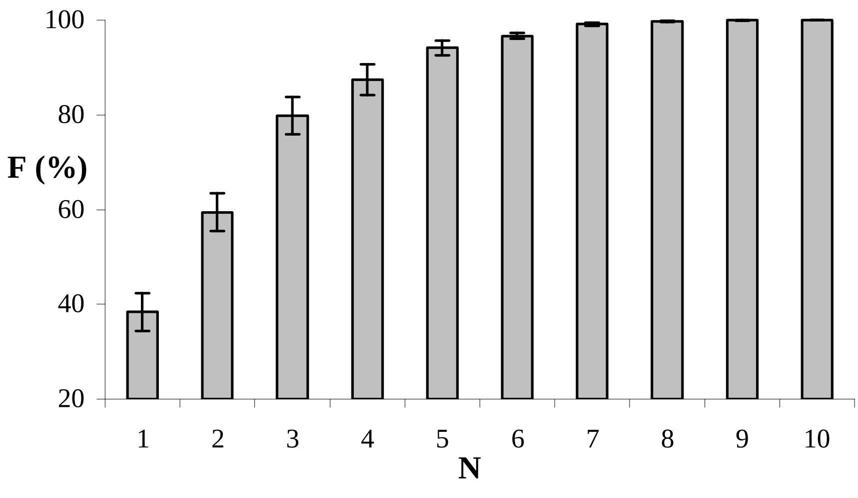

Figure 6.14: The magnetic removal of seven-day weathered crude oil from duck feathers, F (%), as a function of the number of treatments, N, using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 37 in Appendix 6.

For removal from duck feathers, Fig. 6.14, the initial pick-up is ca. 38.3% and, after 7 treatments, a removal of ca. 99.1% is achieved. After 10 treatments only, the maximum removal is 99.9%. For removal from penguin feathers, Fig. 6.15, the initial pick-up is ca. 18.7% and, after 14 treatments, a maximum removal of ca. 99.1% is achieved.

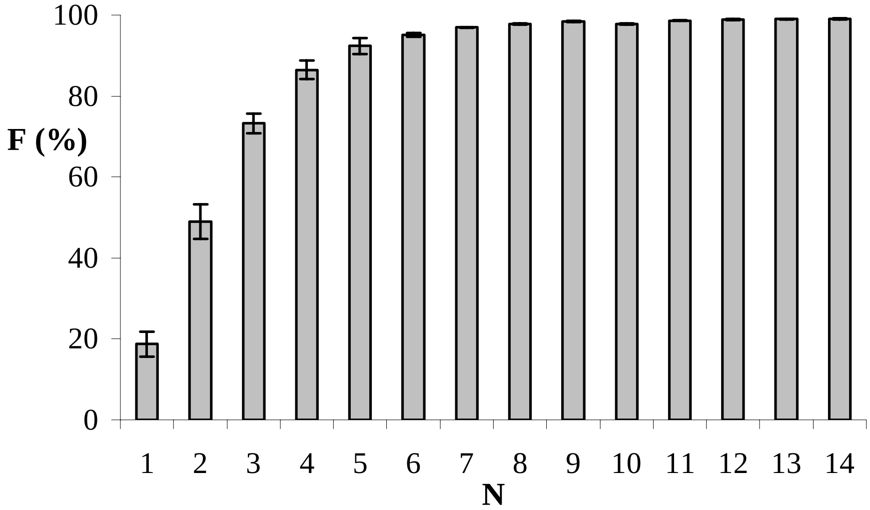

Figure 6.15: The magnetic removal of seven-day weathered crude oil from penguin feathers, F (%), as a function of the number of treatments, N, using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 38 in Appendix 6.

Bunker oil: Analogous experiments to the above were conducted with respect to weathered bunker oil (BO2). For duck feathers, Fig. 6.16, the initial pick-up is ca. 26.6% and a maximum removal of ca. 99.6% is attained after only 10 treatments.

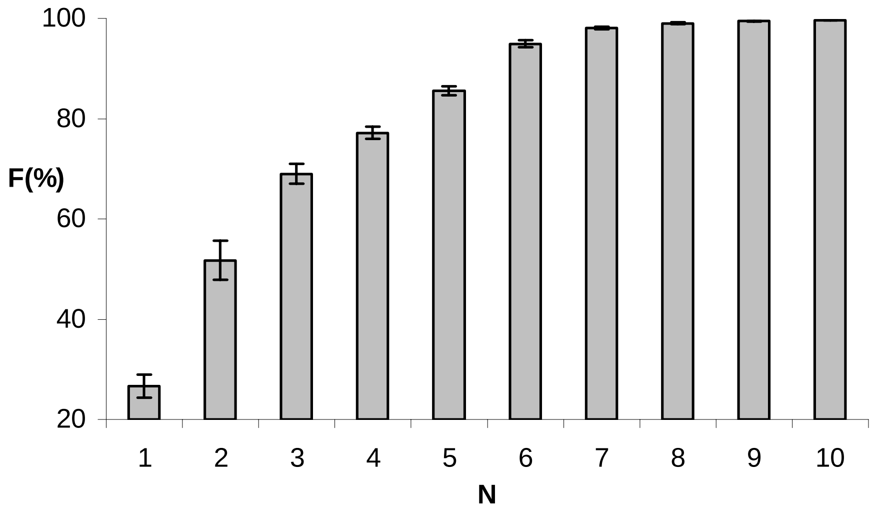

Figure 6.16: The magnetic removal of fourteen-day weathered bunker oil from duck feathers, F (%), as a function of the number of treatments, N, using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 39 in Appendix 6.

For penguin feathers, Fig. 6.17, the initial removal is ca. 36.8% and a maximum removal of ca. 99.1% is achieved after only 10 treatments.

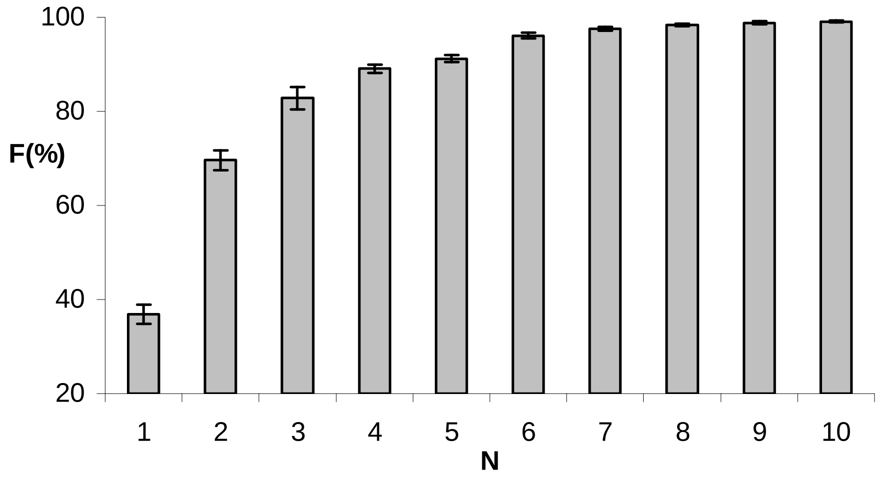

Figure 6.17: The magnetic removal of fourteen-day weathered bunker oil from penguin feathers, F (%), as a function of the number of treatments, N, using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 40 in Appendix 6.

6.2.5.4 Comparison of oil removal with and without the use of olive oil as a pre-conditioner

Crude oil: A comparison between the magnetic removal of seven-day weathered crude oil (SO) from duck and penguin feather clusters was made with and without applying olive oil as a pre-conditioner from N = 6 onwards. The results are shown in Fig. 6.18 and Fig. 6.19.

It is clearly seen from Figs. 6.18 to 6.19 that the application of the olive oil from N = 6 onwards results in a significant improvement in removal from both duck and penguin feathers. More specifically, the maximum removal from duck feathers, with and without olive oil, is 99.99% and 99.35% respectively (significantly different at the 95% confidence level) and the maximum removal from penguin feathers, with and without olive oil, is 99.1% and 97.2% respectively (significantly different at the 95% confidence level). These experiments demonstrate that a judicious use of pre-conditioner can result in an improvement in removal. It was also worth noting that for duck feathers, when using olive oil the maximum removal is achieved earlier at ten treatments, compared to fourteen treatments when not using olive oil. In addition, the use of pre-conditioner results in the removal of discolouration from the feathers. This will be demonstrated in Chapter 7.

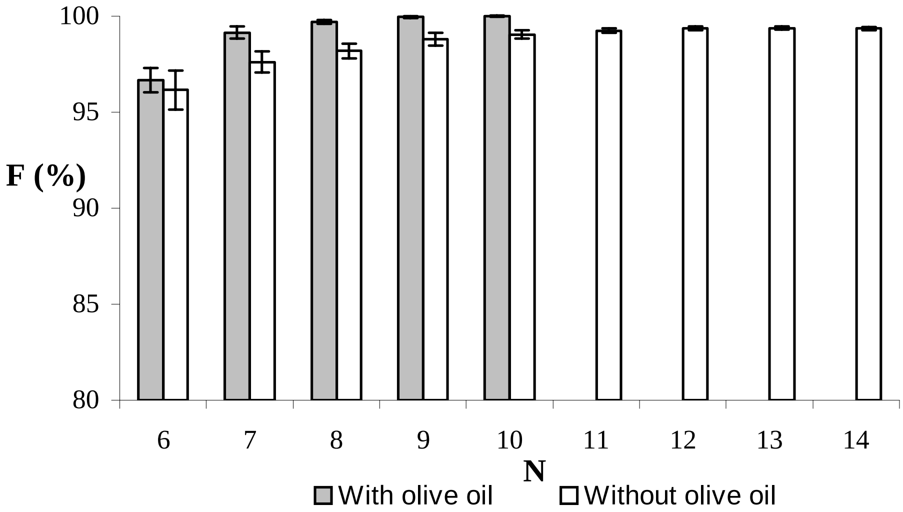

Figure 6.18: Comparison of the magnetic removal of seven-day weathered crude oil from duck feathers, F (%), as a function of the number of treatments, N, with and without using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 41 in Appendix 6.

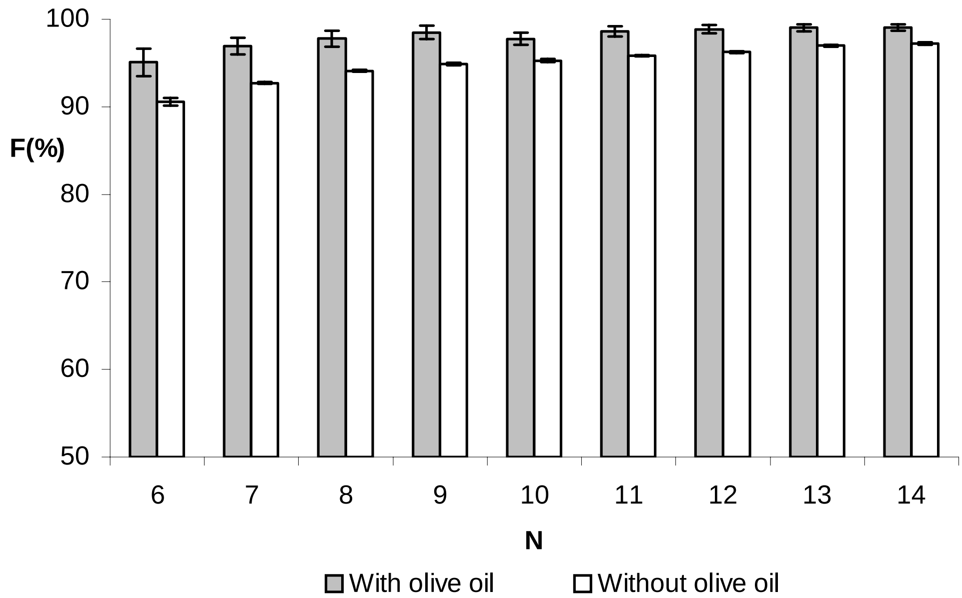

Figure 6.19: Comparison of the magnetic removal of seven-day weathered crude oil from penguin feathers, F (%), as a function of the number of treatments, N, with and without using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 42 in Appendix 6.

Bunker oil: Similarly, a comparison between the magnetic removal of fourteen-day weathered bunker oil (BO2) from duck and penguin feather clusters was made with and without applying olive oil as a pre-conditioner from N = 6 onwards. The results are shown in Figs. 6.20 to 6.21.

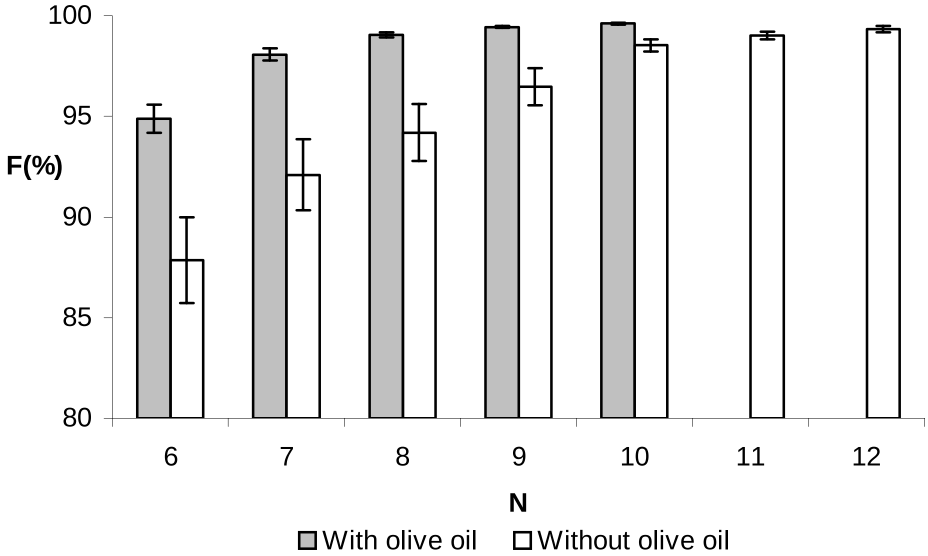

Figure 6.20: Comparison of the magnetic removal of fourteen-day weathered bunker oil from duck feathers, F (%), as a function of the number of treatments, N, between with and without using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 43 in Appendix 6.

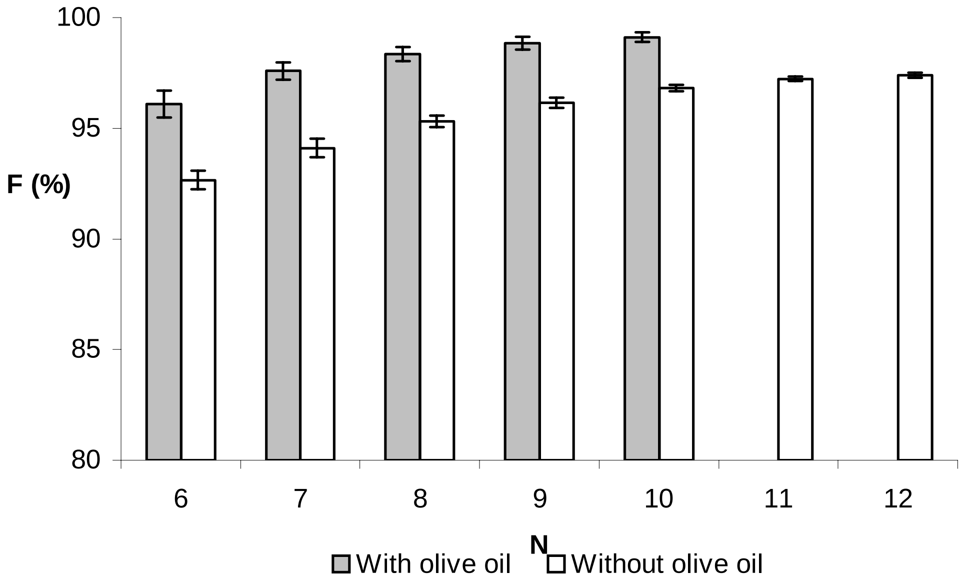

Figure 6.21: Comparison of the magnetic removal of fourteen-day weathered bunker oil from penguin feathers, F (%), as a function of the number of treatments, N, with and without using olive oil as a pre-conditioner from N = 6 onwards. Error bars represent the SE for five replicates. The data are presented in Table 44 in Appendix 6.

It is clearly seen from Figs. 6.20 and 6.21 that the application of the olive oil from N = 6 onwards results in a significant improvement in removal from both duck and penguin feathers, although this is more pronounced for the latter. More specifically, the maximum removal from duck feathers, with and without olive oil, is 99.61% and 99.33% respectively (significantly different at the SE level) and the maximum removal from penguin feathers, with and without olive oil, is 99.11% and 97.40% respectively (significantly different at the 95% confidence level). These experiments demonstrate that a judicious use of pre-conditioner can result in an improvement in removal. It was also worth noting that for both duck and penguin feathers, when using olive oil, the maximum removals are achieved earlier at ten treatments, compared to twelve treatments when not using olive oil. This is very important as less cleaning time causes less stress to the oiled bird that is already exhausted by oiling. In addition, the use of pre-conditioner results in the removal of discolouration from the feathers. This will be further mentioned in Chapter 7.

6.3 Testing on a whole-bird model

6.3.1 Removal of weathered crude oil from plumage

The experimental details for the removal of weathered crude oil from a whole-bird model are described as follows. A penguin carcass was carefully prepared in order to obtain a constant weight in a similar manner to the preparations of carcasses for the fresh and tarry oil experiments (see Chapter 4 and Chapter 5). The weight-stabilized carcass was oiled with molten Shell crude oil (SO) - the same contaminant as used in previous tarry oil experiments. However, unlike those experiments, where the oiled carcass was magnetically cleansed immediately after oiling, in this case the oiled carcass was left for approximately 3 h to ensure full solidification of the residue and to allow preliminary weathering to occur. The time of weathering had to be limited in this case due to occupational health and safety restrictions relating to carcass decomposition. Experiments were carried out by the patch method at a temperature of 295 K, being above the acute temperature (Orbell *et al.*, 2005). The results of these experiments are presented in Fig. 6.22.

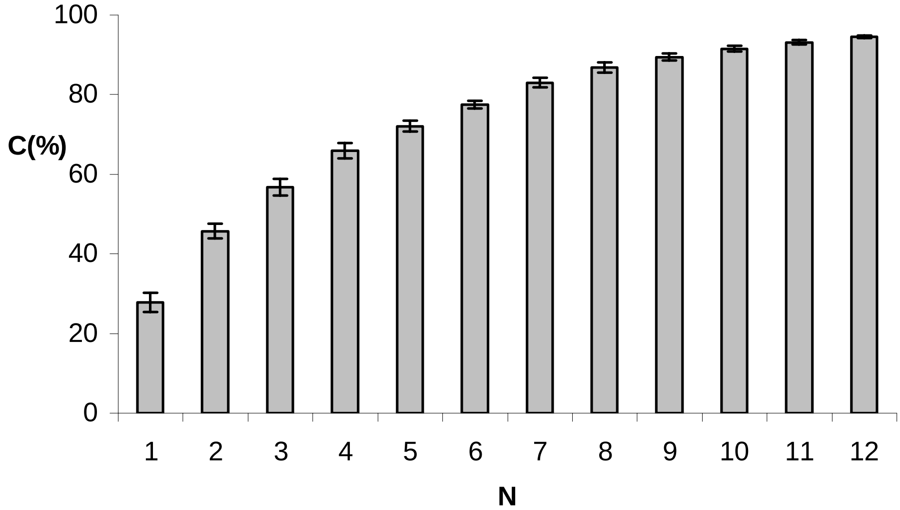

Figure 6.22: The pick-up of weathered crude oil from penguin plumage, C (%), as a function of the number of treatments, N, using the optimal magnetic particles. Error bars represent the SE for five replicates (in patches). The data are presented in Table 45 in Appendix 6.

It can be seen from Fig. 6.22 that after one treatment the removal is quite promising, at ca. 27.8%. The harvesting process is repeated up to 12 times resulting in a maximum removal of ca. 94.5%. This is encouraging, given the fact that the contaminant is semi-solid oil and the cleansing was carried out without using any pre-conditioners. It should be noted that the contaminant, although solidified at this temperature, is slightly wet. This might be expected to help initiate oil sorption onto the iron powder. This should, perhaps, be taken into consideration when dealing with the removal of weathered contamination from wildlife in regions where the ambient temperature is low, thus the provision of heat or the use of a warm pre-treatment agent might be necessary in such circumstances.

6.3.2 Removal of weathered crude oil from plumage using olive oil as a pre-conditioner

Experiments were also conducted on the magnetic removal of weathered crude oil from plumage using olive oil as a pre-conditioner. The experimental details were similar to those presented in Section 6.3.1. Given that the previous experiments on feather clusters had demonstrated that the pre-conditioner was applied from around N = 6 onwards, it was decided to employ this strategy for whole bird models. The pre-weighed carcass was oiled with molten crude oil (SO) and was then left in the laboratory for 3 h. For the first five treatments the weathered oil was removed from the carcass using the iron powder only, i.e. with no pre-conditioner being applied. At N = 6 (i.e. after 5 treatments without pre-conditioner), the oil patch was treated with olive oil and left for 10 min before magnetic cleansing resumed. The harvesting process was then repeated six more times without applying any more olive oil. The results of these experiments are presented in Fig. 6.23.

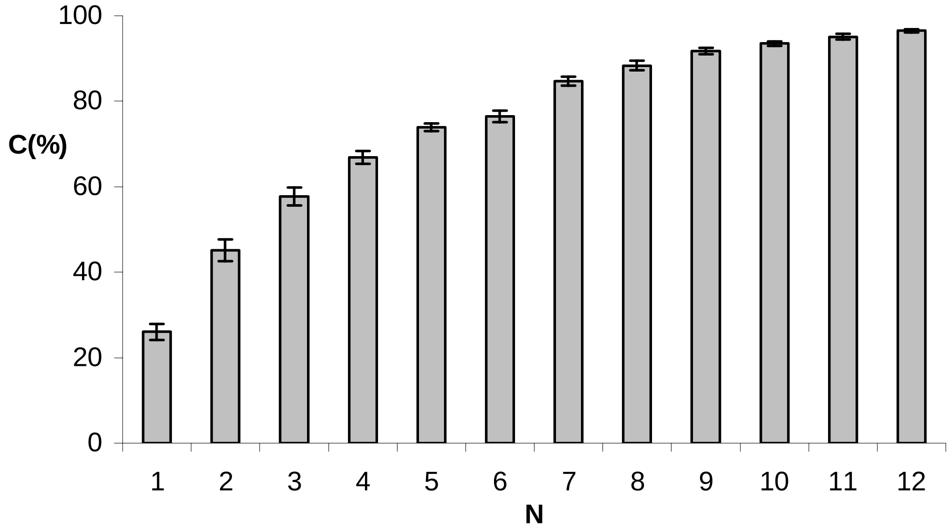

Figure 6.23: The magnetic pick-up of weathered crude oil from plumage, C (%), as a function of the number of treatments, N, using olive oil as a pre-conditioner applied at N = 6. Error bars represent the SE for five replicates (oil applied in patches). The data are presented in Table 46 in Appendix 6.

As can be seen, Fig. 6.23, when olive oil is used at N = 6, one further treatment alone (N = 1) results in ca. 26.0% removal, and after 12 treatments, a maximum removal of 96.5% is achieved.

6.3.3 Comparison of weathered crude oil removal from plumage - with and without the use of olive oil

A comparison of weathered crude oil (SO) from plumage was made with and without the use of olive oil as a pre-conditioner, and the results of these experiments are presented in Fig. 6.24.

In this case, it can be seen that an improvement in removal becomes apparent at N = 7 and culminates in a maximum removal, at N = 12, of 96.4% and 94.5% with and without olive oil, respectively. These values are significantly different at the SE level. Although not as pronounced as with feather clusters, this once again demonstrates the advantage of the *judicious* use of pre-conditioner in cleansing of weathered oiled from plumage.

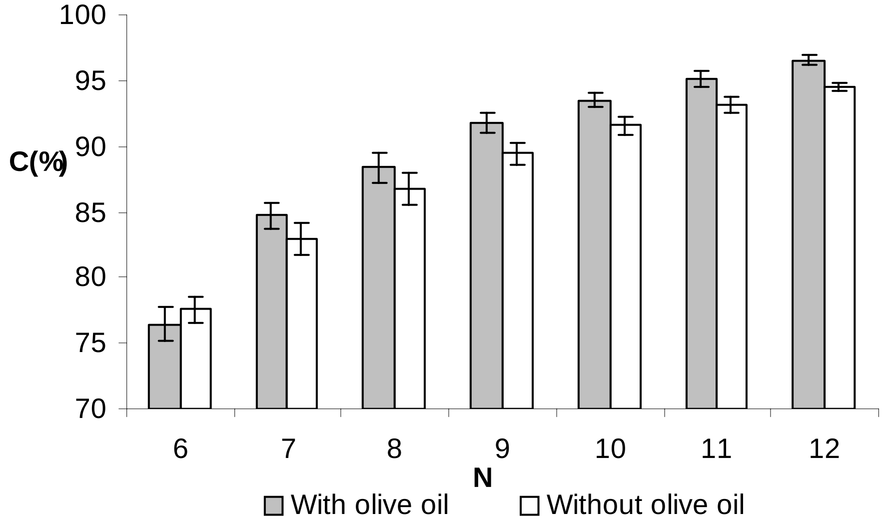

Figure 6.24: Comparison between the pick-up, C (%), of weathered crude oil from plumage as a function of the number of treatments, N, with and without the use of olive oil as a pre-conditioner. Error bars represent the SE for five replicates. The data are presented in Table 47 in Appendix 6.

6.4 Comparison of weathered crude oil removal between feather clusters and plumage

Oil removal experiments that were conducted on penguin carcasses, using one-day weathering, were compared to results obtained for the removal of oil from feather clusters, under the same conditions. A comparative histogram of the results obtained for feather clusters and plumage is presented in Fig. 6.25.

It may be seen in Fig. 6.25 that, for all values of N, the removal of oil is higher for clusters than for plumage. Thus the initial pick-up from feather clusters is 56.7%, significantly higher than 27.8% from plumage. However, the difference becomes less pronounced as the number of treatments increases. In particular, a maximum removal of

97.6% is obtained for feather clusters (after 14 treatments), while the corresponding figure for plumage is 94.5% (after 12 treatments). This is consistent with results for the removal of fresh and tarry oils, which also shows higher removals for feather clusters than for plumage.

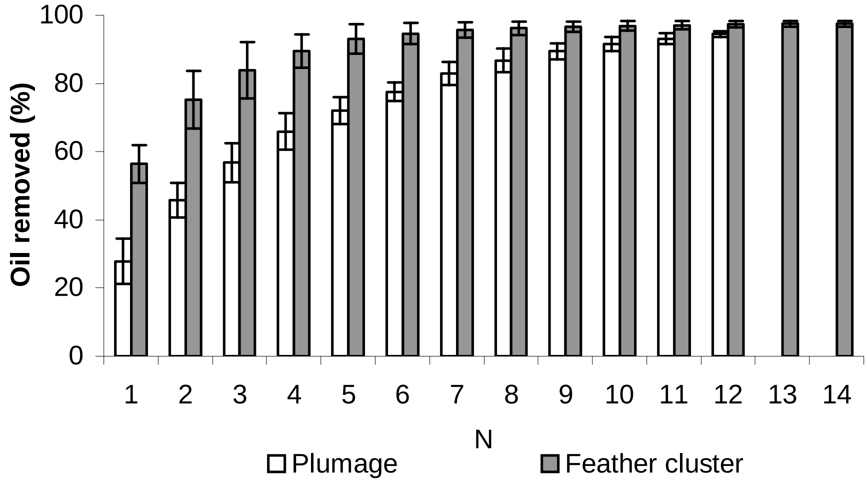

Figure 6.25: Comparison between the removal of weathered crude oil from feather clusters and plumage, using the optimal magnetic particles. Error bars represent the 95% confidence intervals for five replicates. The data are presented in Table 48 in Appendix 6.

6.5 Conclusions

Having been demonstrated to effectively remove fresh and tarry contaminants from feathers and plumage, the optimal iron powder grade was used to remove different weathered contaminants, Shell crude oil (SO) and bunker oil (BO2), from duck and penguin feather clusters and penguin plumage (carcasses).

An investigation into the effect of the time of weathering on the removal of contaminants from both duck and penguin feather clusters was carried out. It was found that for both crude oil and bunker oil, and for duck and penguin feathers, the removal of oil during the first several treatments (particularly the initial treatment) significantly decreases as the time of weathering increases. However, this variation becomes less pronounced as the number of treatments increases. Hence, for both of these contaminants, the maximum pick-up is comparable for all times of weathering, approaching ca. 100% for duck feathers and ca. 98% for penguin feathers. For both types of contaminant, it was also noted that the number of treatments needed to achieve maximum removal from both duck and penguin feathers is less for a shorter time of weathering, e.g. being N = 10 for one-day weathering compared to N = 14 for seven-day and fourteen-day weathering.

A comparison between duck and penguin feathers for the removal of weathered crude oil was carried out. It was found that, for all times of weathering, the removal for the first several treatments is significantly higher for duck feathers than for penguin feathers. The difference, however, becomes less pronounced as the number of treatments increases. Thus the maximum removals become more comparable, even though still significantly higher for duck feathers than for penguin feathers. A similar comparison between duck and penguin feathers was also carried out for weathered bunker oil. Contrary to the crude oil results it was found that, for all times of weathering, the removal of oil after the first several treatments is significantly higher for penguin feathers than for duck feathers. However, the difference, again, becomes less pronounced as the number of treatments increases; with the maximum removals being more comparable and the final removal being significantly higher for duck feathers. Thus there appears to be a complex inter-dependency between weathered oil removal and time of weathering and feather type.

A comparison between crude oil and bunker oil with respect to removal from duck feathers was carried out. It was found that, for one-day and seven-day times of weathering, the oil removal (during the first seven treatments) is generally higher for crude oil than for bunker oil. However, the opposite is found after both oils have been weathered for fourteen days reflecting, perhaps, significant changes in composition. However, the maximum removals achieved for these are essentially equivalent. A similar comparison between crude oil and bunker oil for the removal of oil from penguin feathers was carried out. It was found that, for all times of weathering, the oil removal is lower for crude oil than for bunker oil. Thus in addition to the dependency of removal on time of weathering and feather type, there is also a complex dependency on contamination.

An investigation into the candidacy of olive oil as a pre-conditioner in the magnetic removal of weathered oils from feathers was carried out. At first, experiments on the affinity of the optimal iron powder for olive oil itself were conducted. The results indicate that iron powder effectively removes olive oil, showing a removal of ca. 100% from both a glass substrate and duck feathers.

Different methods were trialled to explore the way in which olive oil can be most effectively applied as a pre-conditioner in the magnetic harvesting process, in relation to weathered contaminants. Preliminary testing suggested that the procedure most likely to give an optimum outcome involves the application of olive oil at N = 6 and then once more at N = 10, if required. More extensive experiments were then conducted for the magnetic removal of seven-day weathered crude oil from duck and penguin feathers employing olive oil as a pre-conditioner. It was found that the application of olive oil from N = 6 onwards results in a significant improvement in removal from both duck and penguin feathers. It is also worth noting that for duck feathers, when using olive oil, the maximum removal is achieved earlier at ten treatments compared to fourteen treatments when not using olive oil. Similar experiments were conducted for the removal of fourteen-day weathered bunker oil from duck and penguin feathers using olive oil as a pre-conditioner. It was found that the application of olive oil from N = 6 onwards also results in a significant improvement in weathered oil removal from both duck and penguin feathers, the improvement being more pronounced for the latter. Again, for both duck and penguin feathers, the use of olive oil leads to the maximum removal being achieved earlier at ten treatments compared to twelve or fourteen treatments than when not using olive oil. It was also noted that for both contaminants and types of feathers the use of olive oil leads to the removal of discolouration. Therefore, it is demonstrated that the judicious use of pre-conditioner can offer real advantages.

As with feather clusters, experiments were carried out with respect to the magnetic removal of weathered crude oil from plumage (penguin carcasses) - with and without using olive oil. When olive oil is not used, the maximum removal from plumage is around 94.5%, although quite promising, still lower than 96.5% when using olive oil. This is consistent with what is achieved with feather clusters, i.e. an improved removal with the use of olive oil.

A comparison between feather clusters and plumage, with respect to the removal of one-day weathered crude oil, was also conducted. It was clear that the removal, especially the initial removal, is considerably higher for feather clusters than for plumage. This is consistent with the results obtained for fresh and tarry contaminants (Chapter 4 and Chapter 5), which show higher removal for feather clusters than for feather plumage. This is not surprising given that plumage is a less accessible matrix. The accessibility might be improved by the application of iron powder in a stream of compressed air.

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CHAPTER 7: THE APPLICATION OF MAGNETIC PARTICLE TECHNOLOGY TO THE SCREENING OF PRE-TREATMENT (CONDITIONING) AGENTS

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CHAPTER 7: THE APPLICATION OF MAGNETIC PARTICLE TECHNOLOGY TO THE SCREENING OF PRE-TREATMENT (CONDITIONING) AGENTS

7.1 Introduction

The use of pre-treatment (conditioning) agents is usually necessary for the cleaning of tarry or weathered oils from feathers or fur (OWCN, 1999; 2003; Hill, 1999). A variety of pre-conditioners have been used or trialed. These include mineral oil (liquid paraffin) (Berkner *et al.*, 1977; Randall *et al.*, 1980; Hill, 1999), methyl oleate (Bryndza *et al.*, 1991; OWCN, 1999; 2003; USFWS, 2002; Walraven, 1992, 2004; Gregory, 2006), Canola oil (OWCN, 1999; 2003; USFWS, 2002; TSBRR, 2005; Gregory, 2006), olive oil (Hill, 1999; OWCN, 1999; 2003) and de-oiler (BD1) (Strauss, *Personal communication*). However, the pre-conditioners themselves also need to be removed during the cleaning process to prevent the problem of replacing an existing contaminant by a new one (Frink and Crozer-Jones, 1986; USFWS, 2002). Although pre-conditioners are reported to improve the removal of oil from feathers or fur (OWCN, 1999; 2003; USFWS, 2002), with some being touted as better than others, the reported improvement is usually anecdotal or based on observation alone and is not quantified.

The optimal iron powder identified in this thesis has been demonstrated to excel in the removal of both fresh and tarry oils from feathers - as discussed in Chapters 4 and 5. In Chapter 6 the use of olive oil as a pre-conditioner in conjunction with this grade of iron powder demonstrated that the use of a pre-conditioner in magnetic cleansing could also be advantageous, at least for the removal of weathered contamination. In this chapter, six different pre-conditioners are tested with regard to their efficiency in the magnetic cleansing of two types of weathered contaminant from clusters of duck feathers. The contaminants are Shell crude oil (SO) and bunker oil (BO2), which have been used in the previous experiments. All experiments were conducted at a temperature of ca. 295 K, which is above the acute temperature (Orbell *et al.*, 2005), and in five-fold replicate.

7.2 The removal of weathered crude oil

7.2.1 Experimental details

Materials used are Shell crude oil (SO), duck feathers and pre-treatment agents. The crude oil is tarry and semi-solid at room temperature with a viscosity from 3000 to 4000 cSt at 100 ^{o}C. Therefore, it is considered to represent a "worst case scenario" for weathered contamination in nature. The feathers are clusters of breast/contour feathers from the Mallard Duck (*Anas platyrhynchos*). The various pre-conditioning agents used are olive oil, Canola oil, blended oil (Canola/soybean), de-oiler (BD1), methyl oleate, and "Bio-dispersol". The first three are commercially available and can be purchased at any supermarket. The de-oiler (BD1) is that used in the Southern African Foundation for the Conservation of Coastal Birds (Strauss, *Personal communication*). The last two, methyl oleate and Bio-dispersol, were kindly provided by VicChem Ltd., Australia.

The methodology used in these experiments is very similar to that in Chapter 6, namely: a bottle containing solid crude oil was placed in a warm water bath to melt the oil. The flowing oil was poured into a beaker. A number of feathers clusters were weighed prior to being oiled with this contaminant. These oiled clusters were then left to weather under normal room conditions for seven days. When the oiled feathers were ready for experimentation, they were weighed before being covered with iron powder, and then magnetically cleansed using a magnetic tester. Each oiled feather cluster was magnetically harvested for the first five treatments without pre-conditioner and was then, at N = 6, saturated with the pre-conditioning agent to soften the remaining tarry residue and left to hang for 10 min to drain off the excess pre-conditioner. Magnetic harvesting was then resumed until the maximum removal was achieved.

7.2.2 Results and discussion

A comparison between the percentage of seven-day weathered crude oil removals from duck feather clusters for six different pre-conditioning agents and for no pre-conditioning agent is presented in Fig. 7.1.

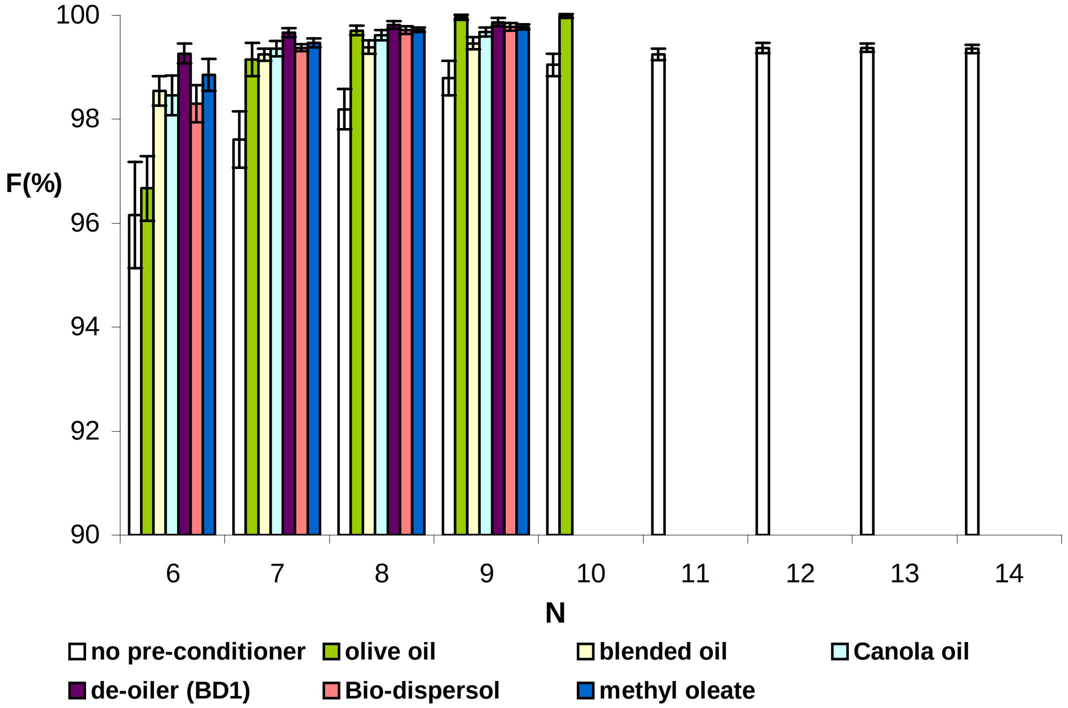

Figure 7.1: Comparison between the percentage of removal, F (%), of weathered crude oil from duck feathers as a function of the number of treatments, N, using various pre-conditioners and without pre-conditioner. Error bars represent the SE for five replicates. The data are given in Table 1 in Appendix 7. The individual profiles are presented from Tables 2 to 8 in Appendix 7.

As can be seen from Fig. 7.1, the pre-conditioner is introduced at N = 6 resulting in an enhanced contaminant removal. Specifically, at N = 6, when no pre-conditioner is used the removal is 96.2% compared to removals exceeding 98% when a pre-conditioner is applied. *Notably, different pre-conditioners result in different degrees of improvement*, the most effective at N = 6 being the de-oiler (BD1) at 99.3%. After 9 treatments, for all pre-conditioners tested, the removal is ca. 100%. This is higher than the removal of 99.4% in the absence of a pre-conditioner. This clearly demonstrates that the use of a pre-conditioner improves oil removal for this particular contaminant. It is also worth noting that when a pre-conditioner is applied in this way, the maximum removal is achieved earlier (after 9 treatments) compared to 14 treatments in the absence of a pre-conditioner. An added bonus of using a pre-conditioner is the removal of feather discolouration, Fig. 7.2. *Significantly, these experiments suggest a means for quantifying the relative efficiency of different pre-conditioners*, see Sections 7.2.3 and 7.2.4.

Figure 7.2: Clusters of duck feathers of weathered crude oil after magnetic cleansing: (0) without using pre-conditioner; using (1) olive oil; (2) blended oil; (3) Canola oil; (4) de-oiler (BD1); (5) methyl oleate; (6) Bio-dispersol.

7.2.3 A means for comparing the relative efficiency of different pre-conditioners

One approach for establishing a quantitative measure for the relative efficiency of different pre-conditioners (for example, in the removal of seven-day weathered crude oil from duck feathers) is to identify an arbitrary *effective number of treatments*, $N_{99,}$ needed to achieve 99% removal. According to this criterion the lower the N_{99} value, the more efficient is the pre-conditioning agent. Fig. 7.3 gives an indication of the relative values for N_{99} for the six pre-conditioners tested compared to the value in the absence of a pre-conditioner. It should be noted that each experiment has been carried out in five-fold replicate (Fig. 1 in Appendix 7). This allows mean values for N_{99} to be calculated with their corresponding error bars; these are presented in Fig. 7.4.

As can be seen from Fig. 7.4, the de-oiler (BD1) is significantly more efficient than the other pre-conditioners. Methyl oleate is significantly more efficient than Bio-dispersol, blended oil and olive oil. Canola oil, Bio-dispersol and blended oil are comparable in their efficiency, within experimental error. Olive oil is, in general, the least efficient of all of the pre-conditioners tested. These results demonstrate that all pre-conditioners tested improve the efficacy of removal by magnetic cleansing, *albeit* to different extents. Furthermore, this approach allows new candidates to be tested and compared.

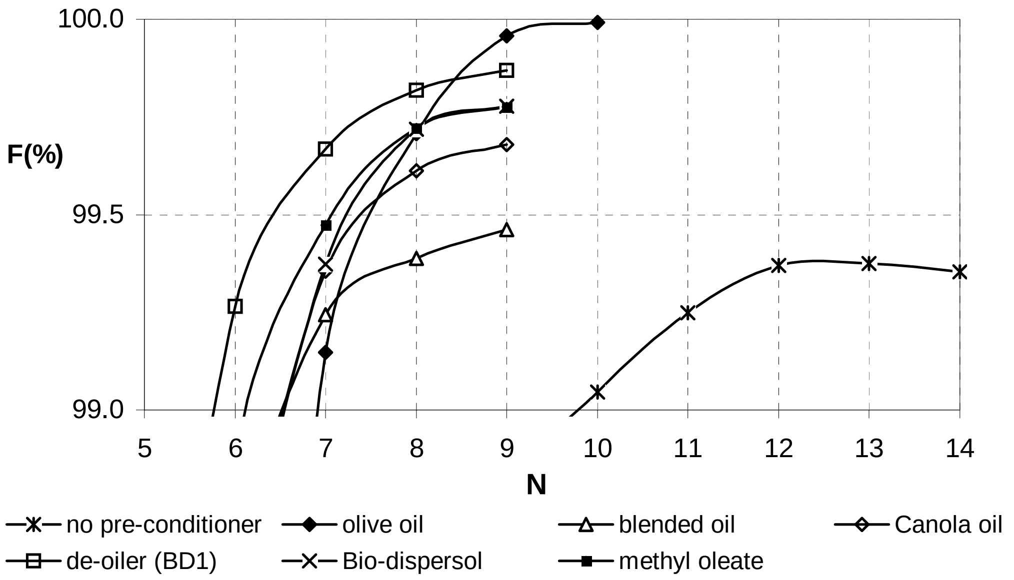

Figure 7.3: Percentage of removal, F (%), of weathered crude oil from duck feathers versus the number of treatments, N, showing the relative values of N_{99} (intercepts on the N axis) for the six pre-conditioners tested, compared to the value in the absence of a pre-conditioner.

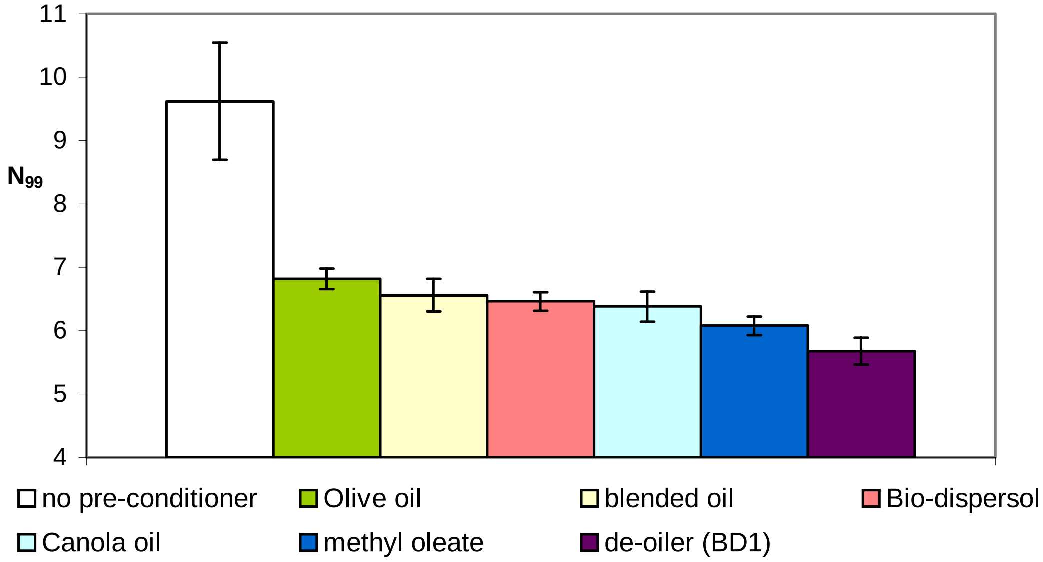

Figure 7.4: Relative average values of N_{99} for the six pre-conditioners tested compared to the average N_{99} value in the absence of a pre-conditioner. Error bars represent the SE for five replicates. The data are presented in Table 9, Appendix 7.

7.2.4 Evaluating the relative efficiency of pre-conditioners using an empirical model

Another approach to evaluating the relative efficiencies of pre-conditioners (for example, in the removal of seven-day weathered crude oil from duck feathers) is to employ the adapted empirical model presented in Chapter 4. This method was used for comparing the removal efficiencies of different fresh contaminants from feathers and is described as follows:

A parameter, $k_{C,}$ (subscript C denotes "crude") is defined that represents the removal efficiency. The greater the value of $k_{C,}$ the more efficient the pre-conditioner. The value of k_C is evaluated from the slope of a plot of - ln(1 - F/F_o) versus N. However, it is worth noting that since the pre-conditioner is introduced approximately halfway through the magnetic cleansing process (at N = 6), the model is only applied from N = 6 onwards. The parameter is, therefore, considered to be only approximate as it is evaluated based on restricted data points. For seven-day weathered crude oil, such a plot (using olive oil as a pre-conditioner) is shown in Fig. 7.5. The plots corresponding to the other pre-conditioners and without pre-conditioner are shown in Figs. 2 to 7, Appendix 7. The calculated relative k_C values are given in Fig. 7.6.

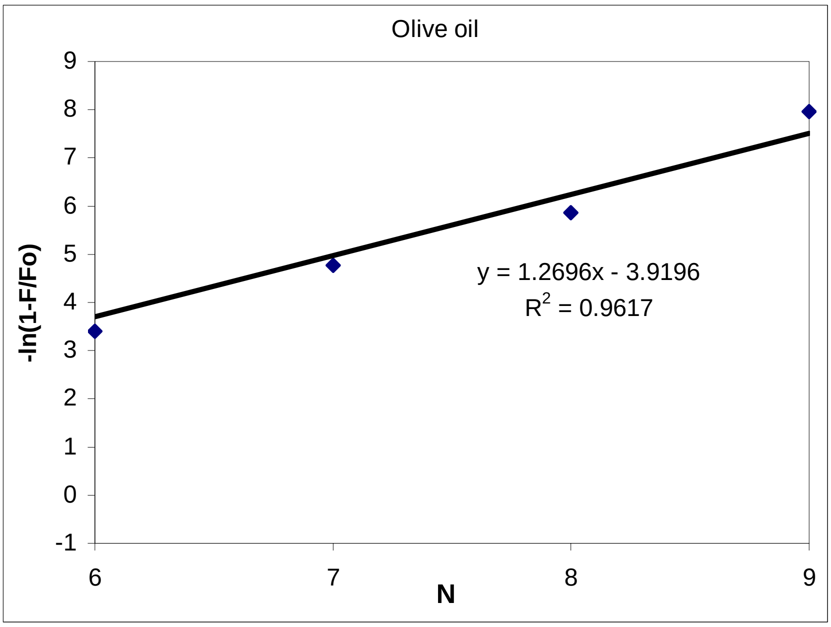

Figure 7.5: Plot of -ln(1 - F/F_o) versus the number of treatments, N, for the removal of weathered crude oil from duck feathers using olive oil as a pre-conditioner.

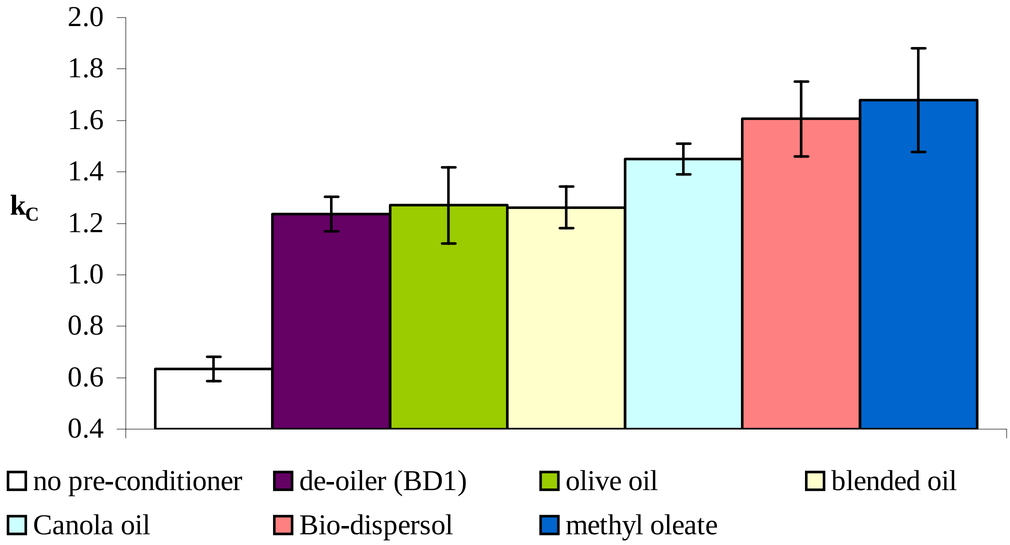

Figure 7.6: Relative values of k_C for the six pre-conditioners tested compared to the k_C value in the absence of a pre-conditioner. Error bars represent the SE of the slope (Kirkup, 1994). The data are presented in Table 10, Appendix 7.

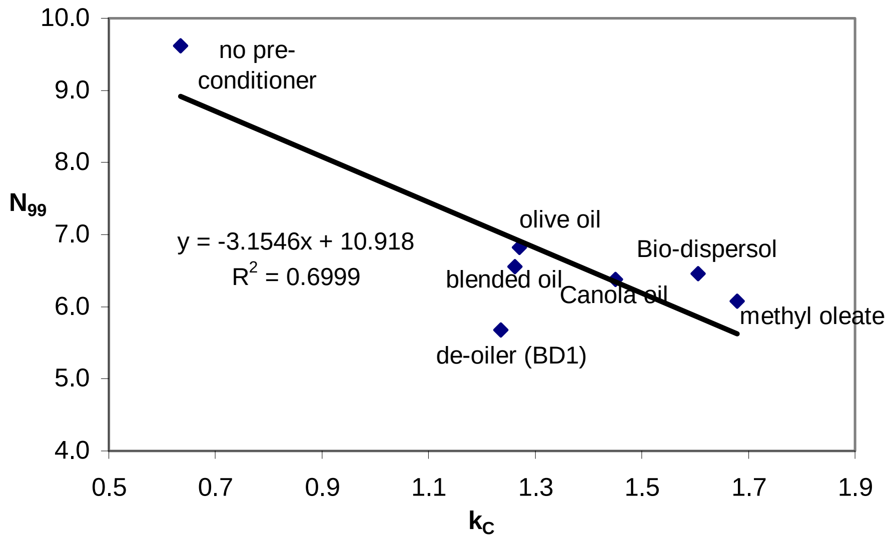

Figure 7.7: Correlation between N_{99} and k_C for the six pre-conditioners tested and in the absence of a pre-conditioner in the magnetic cleansing of weathered crude oil from duck feathers.

It may be seen from Fig. 7.6 that, in general, methyl oleate and Bio-dispersol are significantly more efficient than blended oil, olive oil and de-oiler (BD1). Canola oil is significantly more efficient than blended oil and de-oiler (BD1), but comparable with olive oil. Blended oil, olive oil and de-oiler (BD1) are, within experimental error, comparable in efficiency. When no pre-conditioner is used, the value of k_C is significantly lower than any of the k_C values obtained when pre-conditioners are employed, indicating that the use of a pre-conditioner improves oil removal. Therefore, with the exception of de-oiler (BD1), the results from the empirical model are found to be consistent with the N_{99} results, as indicated by the correlation between the k_C and N_{99} values, Fig. 7.7.

7.3 The removal of weathered bunker oil

7.3.1 Experimental details

Similarly, experiments have been conducted to compare the efficiencies of magnetic removal of fourteen-day weathered bunker oil from duck feather clusters, amongst the above six pre-conditioners and without pre-conditioner. This contaminant is bunker oil (BO2 in Table 2.2, Chapter 2), that is a highly viscous oil (222 cSt at 40 ^{o}C) and is sometimes encountered as a contaminant at the Phillip Island Nature Park, posing threats to the Little Penguin colony (Jessop, *Personal communication*). The methodology to carry out these experiments is similar to that presented in the previous section for crude oil, however, in this case it was not necessary to heat the oil prior to experimentation as it is a liquid at room temperature. The oiled duck feather clusters were left to weather in normal room conditions for fourteen days (instead of seven days as in the case of crude oil). This represents a worst-case scenario contamination.

7.3.2 Results and discussion

A comparison between the percentage of fourteen-day weathered bunker oil removals from duck feather clusters for six different pre-conditioning agents and for no pre-conditioning agent is presented in Fig. 7.8. As with crude oil, the pre-conditioner is introduced at N = 6 resulting in an enhanced contaminant removal. Specifically, at N = 6, when no pre-conditioner is used the removal is 87.9% compared to removals exceeding 94% when a pre-conditioner is applied. *Notably, again, different pre-conditioners result in different degrees of improvement*, the most effective at N = 6 being methyl oleate at 98.7%. After ten treatments, for all pre-conditioners tested, the removal is ca. 100%. This is higher than the removal of 99.3% in the absence of a pre-conditioner. Again, this clearly demonstrates that the use of pre-conditioner improves oil removal for this particular contaminant. It is also worth noting that when a pre-conditioner is applied in this way, the maximum removal is achieved earlier (after 10 treatments) compared to 12 treatments in the absence of a pre-conditioner. As with crude oil, the use of a pre-conditioner results in the removal of feather discolouration, Fig. 7.9.

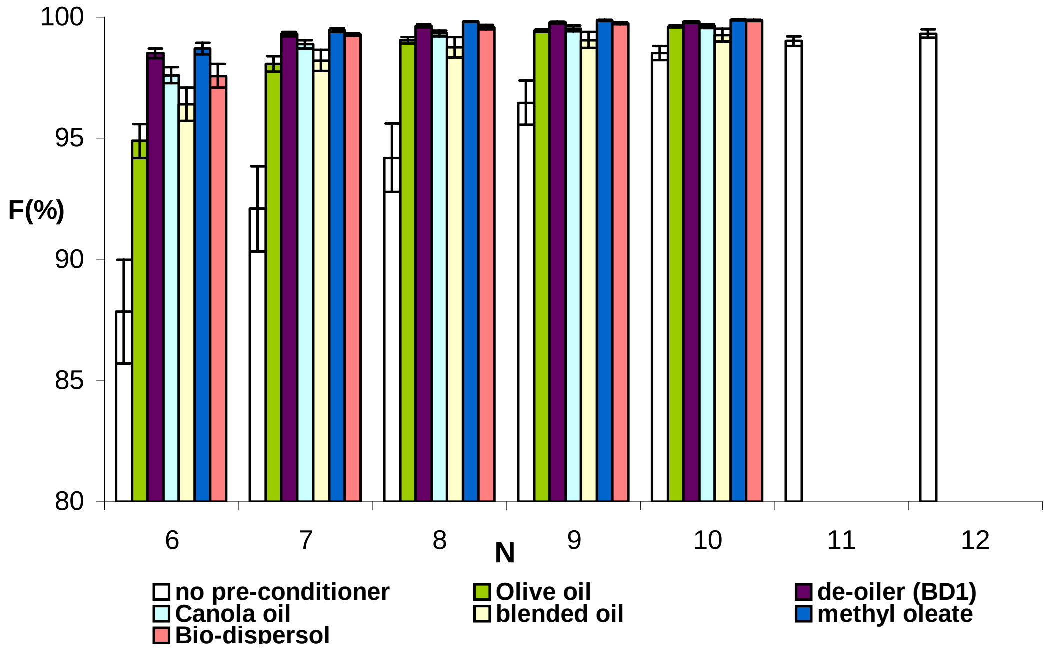

Figure 7.8: Comparison of the percentage of removal, F (%), of weathered bunker oil from duck feathers with and without the use of pre-conditioning agents as a function of the number of treatments, N. Error bars represent the SE for five replicates. The data are given in Table 11 in Appendix 7. The individual profiles are presented in Tables 12 to 18 in Appendix 7.

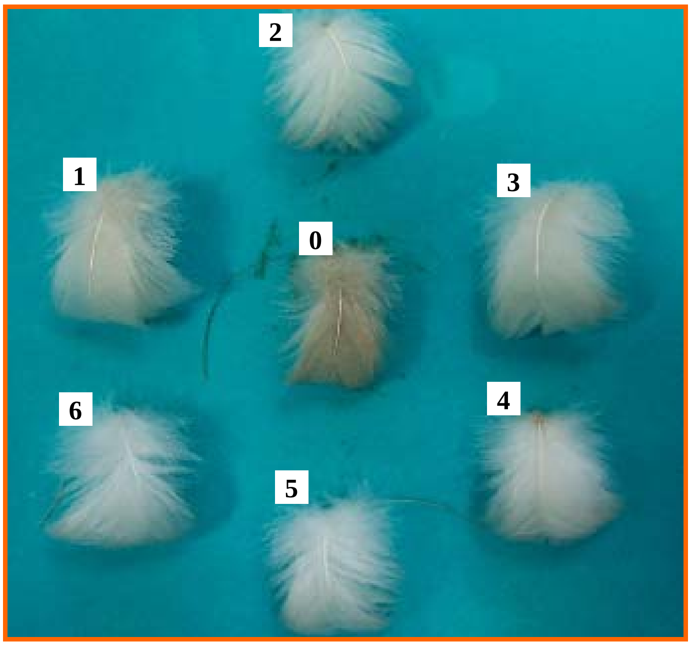

Figure 7.9: Clusters of duck feathers previously contaminated with weathered bunker oil after magnetic cleansing: (0) without using pre-conditioner; using (1) olive oil; (2) blended oil; (3) Canola oil; (4) de-oiler (BD1); (5) methyl oleate; (6) Bio-dispersol.

7.3.3 A means for comparing the relative efficiency of different pre-conditioners

As with crude oil (Section 7.2.3), the *effective number of treatments*, N_{99}, was also employed to compare the efficiency of magnetic removal of fourteen-day weathered bunker oil from duck feathers using different pre-conditioners. Fig. 7.10 gives an indication of the relative values for N_{99} for the six pre-conditioners tested compared to the value in the absence of a pre-conditioner. The accurate value for N_{99} and its corresponding error bars of each pre-conditioner was calculated using the technique indicated in Appendix 7 (see, for example, Fig. 8 in Appendix 7). The results of N_{99} for all of the pre-conditioners tested and for no pre-conditioner are presented in Fig. 7.11.

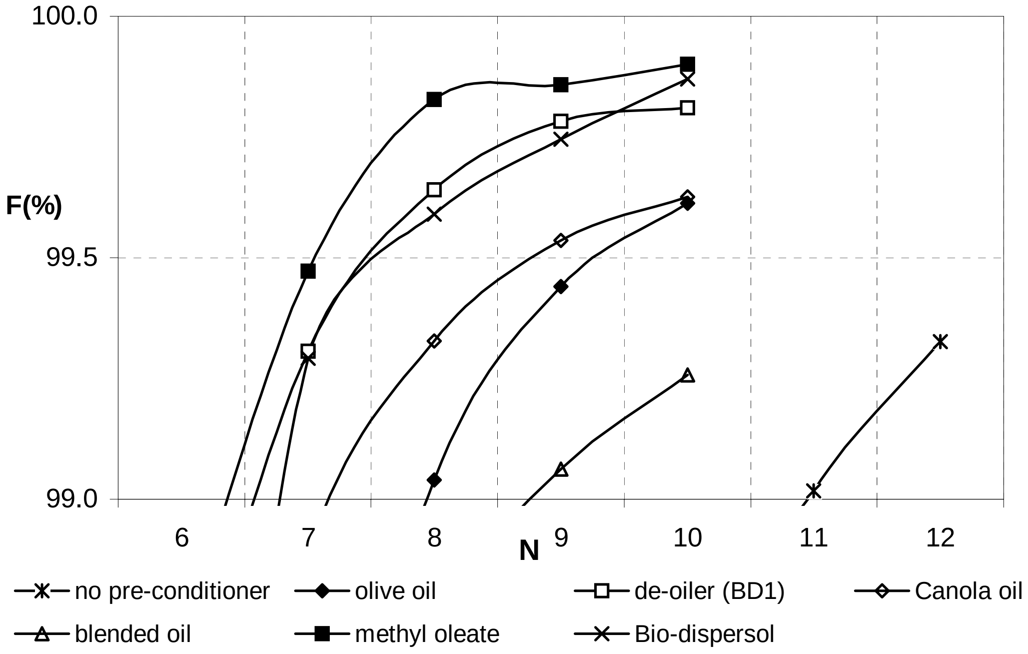

Figure 7.10: Percentage of removal, F (%), of weathered bunker oil from duck feathers versus the number of treatments, N, showing the relative values of N_{99} (intercepts on the N axis) for the six pre-conditioners tested, compared to the value in the absence of a pre-conditioner.

As can be seen from Fig. 7.11, methyl oleate is significantly more efficient than all of the other pre-conditioners except de-oiler (BD1) that is significantly more efficient than Canola oil, olive oil and blended oil. In general, methyl oleate is the most efficient with blended oil being the least efficient of all of the pre-conditioners tested. As with crude oil, when not using pre-conditioner, the N_{99} value is significantly higher than that when pre-conditioners are used, indicating that the use of a pre-conditioner improves oil removal.

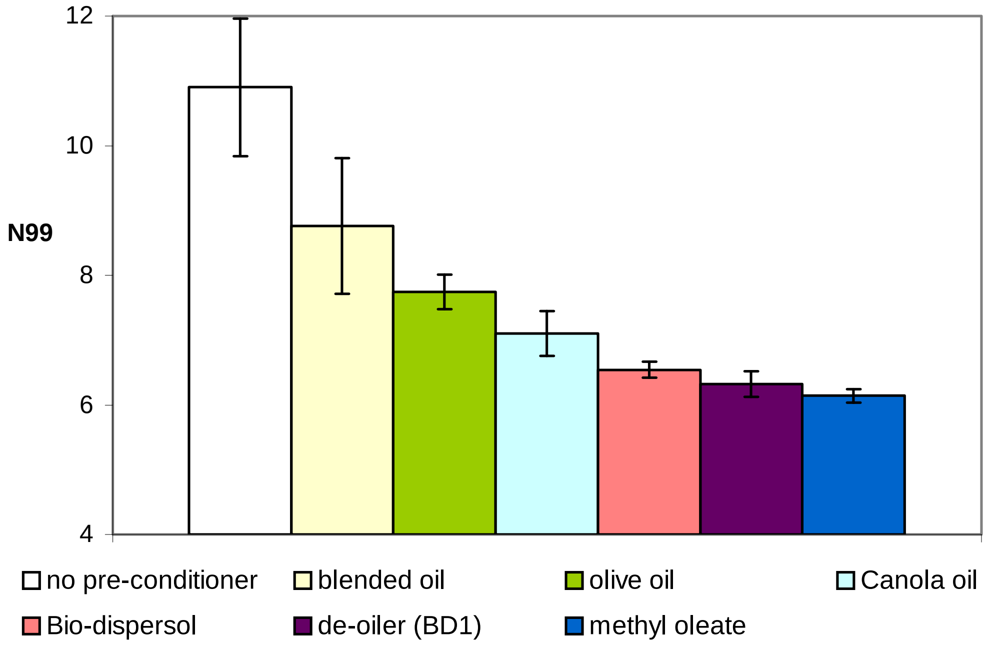

Figure 7.11: Relative average values of N_{99} for the six pre-conditioners tested compared to the average N_{99} value in the absence of a pre-conditioner. Error bars represent the SE for five replicates. The data are presented in Table 19 in Appendix 7.

7.3.4 Evaluating the relative efficiency of pre-conditioners using an empirical model

As with crude oil (Section 7.2.4), the same adapted empirical model is employed to compare the magnetic removal efficiency, representing by k_B, (subscript B denotes "bunker") of fourteen-day weathered bunker oil from duck feathers with different pre-conditioners and without using pre-conditioner. For this contaminant, a plot of -ln(1 - F/F_o) versus N (N = 6 onwards) using olive oil is shown in Fig. 7.12. The remaining plots for the other pre-conditioners and without using pre-conditioner are presented in Figs. 9 to 14, Appendix 7. The values of k_B for different pre-conditioners and without using pre-conditioner are shown in Fig. 7.13.

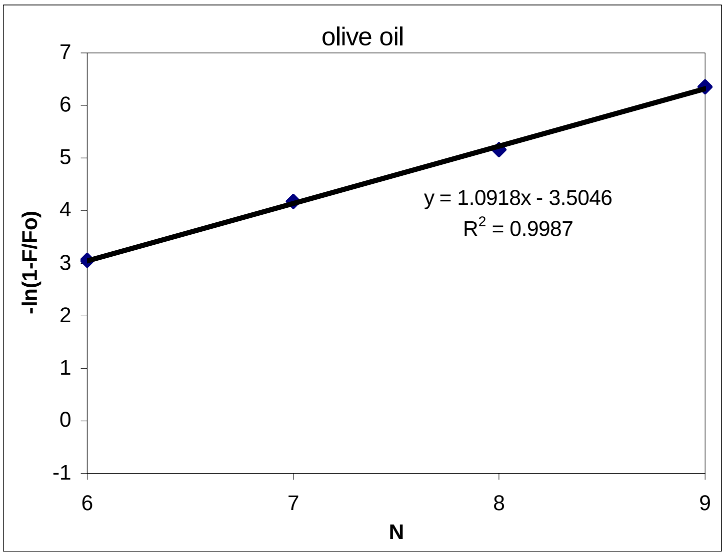

Figure 7.12: Plot of -ln(1 - F/F$_o$) versus the number of treatments, N, for the removal efficiency of weathered bunker oil from duck feathers using olive oil as a pre-conditioner.

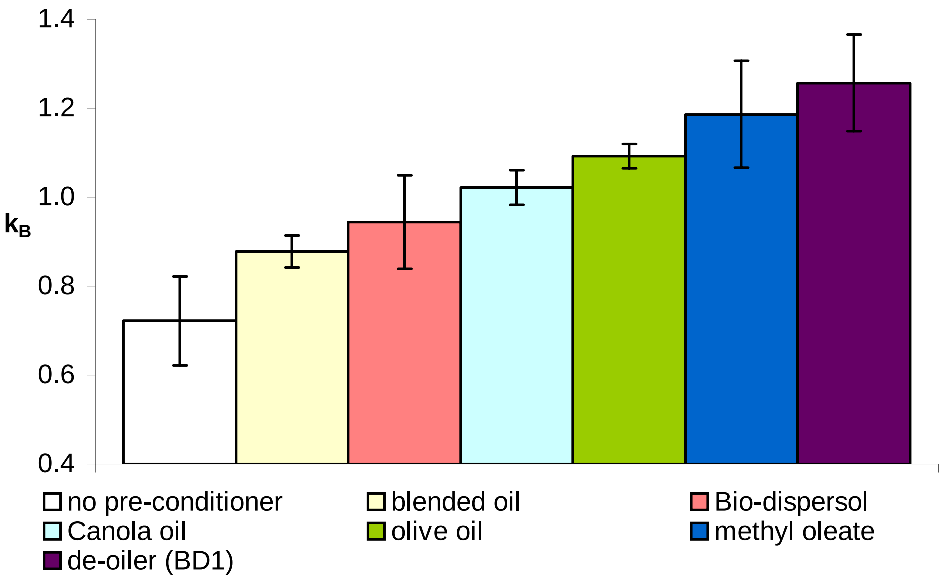

Figure 7.13: Relative values of k_B for the six pre-conditioners tested compared to the k_B value in the absence of a pre-conditioner. Error bars represent the SE of the slope (Kirkup, 1994). The data are presented in Table 20, Appendix 7.

As can be seen from Fig. 7.13, de-oiler (BD1) is significantly more efficient than the other pre-conditioners except methyl oleate, which is significantly more efficient than Canola oil, Bio-dispersol and blended oil. Bio-dispersol and blended oil are comparable, within experimental error. In general, de-oiler (BD1) and methyl oleate are more efficient than the others, and blended oil appears to be the least efficient. When no pre-conditioner is used, the k_B value is significantly lower than any of the k_B values when using pre-conditioners, indicating that the use of a pre-conditioner improves oil removal. As with crude oil, the results from the empirical model approach are, with the exception of Bio-dispersol, quite consistent with the effective number of treatment approach. This is demonstrated by the correlation between k_B and N_{99}, Fig. 7.14.

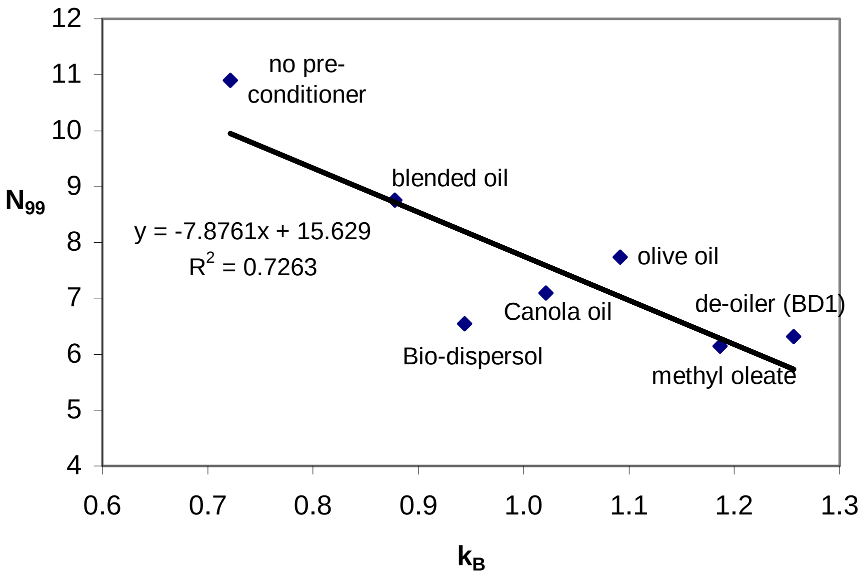

Figure 7.14: Correlation between N_{99} and k_B for the six pre-conditioners tested and in the absence of a pre-conditioner in the magnetic cleansing of weathered bunker oil from duck feathers.

7.4 Comparison between different contaminants with respect to removal efficiencies as measured by N_{99} and k

A comparison of the removal efficiencies, as measured by both N_{99} and k, between weathered crude oil and bunker oil was made with respect to each of the pre-conditioners tested, and in the absence of pre-conditioner, Fig. 7.15.

In order to interpret Fig. 7.15, it is important to note that there is an inverse relationship between N_{99} and k, Fig. 7.7 and Fig. 7.14. In other words, the lower the value of N_{99} the better the removal and conversely for k. In general, it may be observed from both indicators that the order of efficiencies of the pre-conditioners is different between the two contaminants, suggesting that there is some contaminant dependency upon pre-conditioner efficiency. For example, both indicators show that olive oil is the least efficient pre-conditioner for crude oil (SO), whilst it is blended oil for bunker oil (BO).

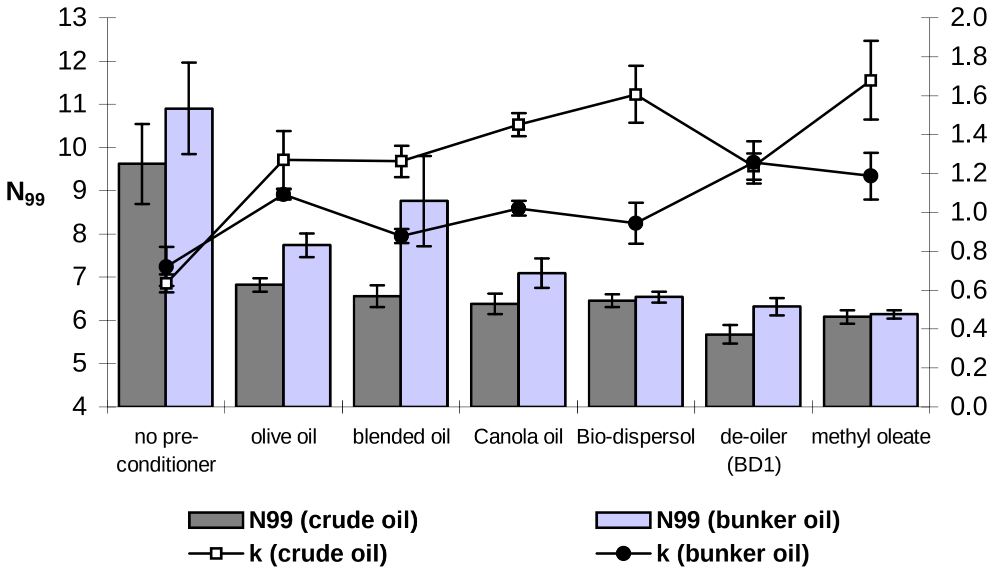

Figure 7.15: Comparison between crude oil and bunker oil with respect to the N_{99} and k values for different pre-conditioners and without pre-conditioner. Error bars represent SE. The data are presented in Table 21 in Appendix 7.

It was also observed that most of the pre-conditioners are better for crude oil (SO) than for bunker oil (BO2). Specifically, for olive oil, blended oil and Canola oil, both N_{99} and k suggest that the efficiency is higher for crude oil than for bunker oil. However, using N_{99}, for Bio-dispersol and methyl oleate, the efficiency is found to be comparable for crude oil and bunker oil. However, using k, for these pre-conditioners the efficiency is found to be better for crude oil. Thus, these two pre-conditioners can also be said to be more efficient for crude oil than for bunker oil. Regarding de-oiler (BD1), while N_{99} suggests that the efficiency is higher for crude oil than for bunker oil, k shows comparable efficiencies between the two. Therefore, we conclude that de-oiler (BD1) is also better for crude oil than for bunker oil. Both indicators also suggest that, for both contaminants, methyl oleate is, in general, more efficient than any of the other pre-conditioners.

Table 7.1 summarises the relative order of pre-conditioner efficiency, based on N_{99} and k parameters, for both contaminants

Table 7.1: Relative order of pre-conditioner efficiency, based on both N_{99} and k parameters, for crude oil (SO) and bunker oil (BO2). Efficiency increases from 1 to 6.

Relative order of efficiency	Crude oil		Bunker oil	
	N_{99}	**k**	**N_{99}**	**k**
6	De-oiler (BD1)	Methyl oleate	Methyl oleate	De-oiler (BD1)
5	Methyl oleate	Bio-dispersol	De-oiler (BD1)	Methyl oleate
4	Canola oil	Canola oil	Bio-dispersol	Olive oil
3	Bio-dispersol	Blended oil	Canola oil	Canola oil
2	Blended oil	Olive oil	Olive oil	Bio-dispersol
1	Olive oil	De-oiler (BD1)	Blended oil	Blended oil

7.5 A pre-conditioner efficiency parameter

A parameter, denoted **E**, derived from the relative pre-conditioner values of $\mathbf{N_{99}}$ (for a given contaminant and a given feather type), *vide supra*, may be defined in order to conveniently compare the relative efficiencies of different pre-conditioners. This parameter is defined as follows:

$$\mathbf{E = 1- N_{99}(with\ pc)/N_{99}(no\ pc)} \qquad (7.1)$$

E = the pre-conditioner efficiency parameter; $\mathbf{N_{99}}$**(with pc)** = the number of treatments required to achieve 99% removal using a given pre-conditioner; $\mathbf{N_{99}}$**(no pc)** = the number of treatments required to achieve 99% removal when no pre-conditioner is used).

Note: the E value in the absence of pre-conditioner is zero, by definition.

Fig. 7.16 shows the relative E values for six different pre-conditioners for the magnetic removal of weathered crude oil from duck feathers. Fig. 7.17 shows the relative E values for six different pre-conditioners for the magnetic removal of weathered bunker oil from duck feathers.

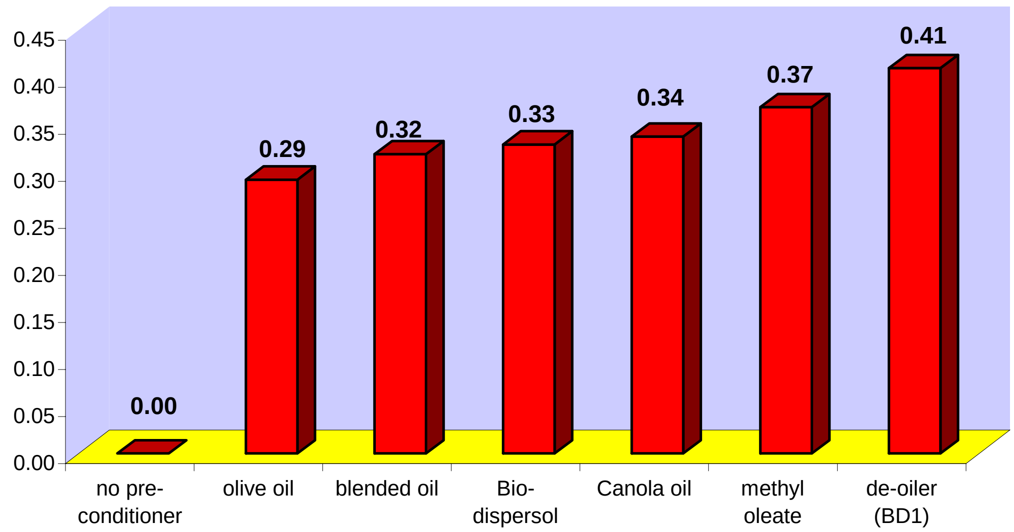

Figure 7.16: Relative E values for six pre-conditioners tested for the removal of weathered crude oil from duck feathers. The data are presented in Table 22, Appendix 7.

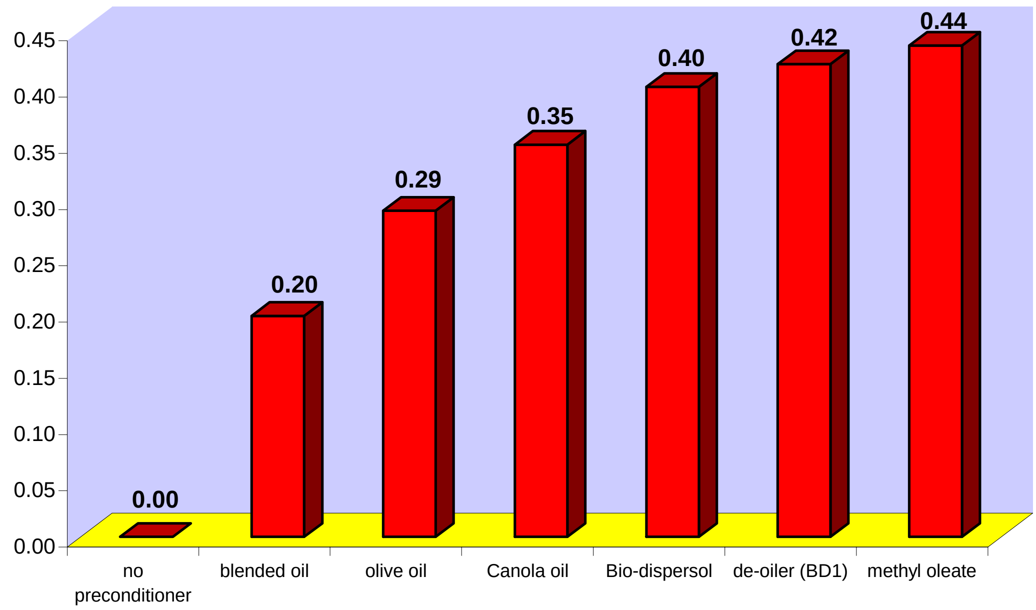

Figure 7.17: Relative E values for six pre-conditioners tested for the removal of weathered bunker oil from duck feathers. The data are presented in Table 22, Appendix 7.

Note that the maximum pre-conditioner efficiency for these experiments is 0.44. This suggests, on a scale of 0 – 1, that there is scope for considerable improvement.

7.6 Conclusions

A methodology was developed to quantify the effect of using pre-conditioners in conjunction with magnetic cleansing. Six different pre-conditioners were tested with respect to the removal of two types of weathered contaminant, namely crude oil (SO) and bunker oil (BO2), from clusters of duck feathers.

It was demonstrated, *quantitatively,* for both contaminants, that the removal is enhanced when a pre-conditioner is applied and that the degree of improvement depends on the type of pre-conditioner used. Notably, for all pre-conditioners tested, a maximum removal ca. 100% is eventually achieved. However, the use of a particular pre-conditioner leads to the maximum removal being achieved earlier - compared to not using a pre-conditioner at all. Indeed, the effective number of treatments at which a defined removal is achieved depends on the particular pre-conditioner, providing a basis for quantifying the relative effectiveness of pre-conditioners. It was also found that the use of a pre-conditioner results in the removal of discolouration from the feathers.

Specifically, in order to quantify the relative efficiencies of pre-conditioners, two parameters were employed. Namely, the effective number of treatments, N_{99}, at which 99% removal is achieved and a parameter, k, derived from an adapted empirical model. The latter parameter is considered to be only approximate given that it is necessarily based on restricted data.

Regarding the removal of weathered crude oil from duck feathers, the N_{99} values indicate that the de-oiler (BD1) is the most efficient of all of the pre-conditioners tested. This is followed by methyl oleate, which, in turn, is more efficient than Canola oil, Bio-dispersol, blended oil and olive oil (found to be the least efficient). For the removal of weathered bunker oil from duck feathers, methyl oleate and de-oiler (BD1) are also the most efficient, followed by Bio-dispersol, Canola oil, and olive oil; with blended oil being the least efficient for this particular contaminant.

Similar orders of efficiencies of the pre-conditioners as above are obtained by using k values in the removal of both contaminants from duck feathers.

Therefore, it is concluded that, to some extent, the relative efficiency of pre-conditioners is contaminant dependent, although for these two contaminants in particular, the preferred pre-conditioners are readily selected based on this assay, as follows: most efficiency (methyl oleate and de-oiler-BD1), medium efficiency (Bio-dispersol and Canola oil) and least efficiency (olive oil and blended oil).

These findings pave the way for the screening of a wide variety of candidates for various pre-conditioner contaminants and substrates.

7.7 References

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CHAPTER 8: SUMMARY AND RECOMMENDATIONS

In recognition of the extreme sensitivity of wildlife, particularly birds, to environmental pollution, this project has endeavoured to advance the science and technology involved in their rescue and rehabilitation. Specifically, this project has been concerned with the development of MPT as a potential improvement over conventional detergent-based methods.

A proven gravimetric methodology has been applied to establishing the important proof of principle that 100% oil removal from feathers can be achieved by varying the physical characteristics of the particles. Having identified an optimal grade of iron powder, this was demonstrated to show superior removal of a range of non-tarry contaminants from duck and penguin feather clusters and plumage. These experiments suggest a means for the further development of optimal particles for a wide range of different applications.

Highly viscous or tarry contamination presents additional challenges to both environmental remediation and oiled wildlife treatment. Although MPT has been shown to be effective at removing a variety of non-tarry contaminants, it has been suggested that tarry or highly viscous oil contamination might prove resistant to the application of the so-called "magnetic cleansing" method. For these reasons, temperature dependent *in vitro* studies were conducted on the ability of the optimal iron powder to magnetically cleanse a highly viscous (tarry) oil from feather clusters (both duck and penguin) and from feather plumage (penguin). A remarkable acute temperature dependency for the removal of this kind of contaminant has been observed whereby, below and at certain temperatures (14 – 16 ºC), that is well below the pour point of the contaminant (ca. 28 ºC), effectively no removal occurs. However, above these temperatures, the removal rapidly approaches 100%. The nature of these experiments has allowed the thermodynamics of the process to be investigated, hence providing an insight into the phenomenon. More specifically, the process has been shown to be highly endothermic and entropy driven. The removal of other types of tarry contaminant from a wide range of feather types remains to be investigated.

Another consideration in the removal of oil contamination in the environment is the phenomenon of weathering. This can significantly change the composition of the contaminant and affect removal characteristics. The present research has systematically investigated this problem with respect to the magnetic cleansing of weathered crude oil (tarry) and heavy bunker oil (non tarry) from feathers (duck and penguin) and plumage (penguin). The results of these studies show that initial removal is reduced with increasing time of weathering but towards the end of the treatment process the removal appears to be independent of the time of weathering. This could have important implications for the field application of the technology, where treatment upon first encounter might be limited to an initial cleansing only. This might be appropriate when large numbers of birds are involved and toxic contaminant removal via magnetic cleansing, prior to traditional detergent-based cleansing, is an important consideration.

The role of pre-conditioners (or pre-treatment agents) used in conjunction with magnetic cleansing was explored in some detail. It was found that the use of such agents accelerates and improves the overall removal. Furthermore, the use of a pre-conditioner results in the removal of discolouration from the feathers. Interestingly, it was found that a pre-conditioner is most effective when applied approximately half way through the treatment process. This is also found to be the case for traditional detergent based cleansing. Six different pre-conditioning agents were tested for their relative effectiveness. It is clear from these studies that some pre-conditioning agents are clearly superior to others for a given feather type and contaminant. These experiments have resulted in an assay (based on MPT) for quantifying the relative effectiveness of pre-conditioning agents for use in either magnetic cleansing or traditional detergent based cleansing. This opens the way for the systematic development of more effective pre-conditioners for given feather types and types of contaminant. Ongoing research envisages the development of a pre-conditioner database that can be accessed by wildlife rehabilitators worldwide.

Appendix 1

1.3 Traditional techniques for oil spill remediation

Due to the serious consequences caused by oil spills, much research has been carried out to develop remediation techniques to deal with this issue (Suni *et al.*, 2004; Ventikos *et al.*, 2004). These techniques generally fall into four categories (Mullin and Champ, 2003; Ventinkos *et al.*, 2004), namely: mechanical/physical recovery (booms, skimmers, sorbents), chemical treatment (dispersants, emulsion breakers; gelling agents, sinking agents) and bioremediation, and in-situ burning.

1.3.1 Physical/mechanical treatment of oil spills

Physical/mechanical methods for oil spill remediation have been utilised for a long time with varying degrees of success (Wei *et al.*, 2003). These methods are used extensively in many countries, including the United States (USEPA-a, 2004) and Australia (Brown, 2003; AMSA, 2004). One of these methods is the booming of oil spills.

1.3.1.1 Booming

Booms are employed to prevent oil from spreading on the water's surface and surround the spill close to the source (ITOPF-a, 2004). Booms are also used to prevent oil from entering harbours, docks or any sensitive areas and to divert the oil spill to an area where operation can be made (NOAA-a, 2004). This method is also employed to concentrate oil in thicker surface layers, facilitating the recovery process (USEPA-a, 2004) since thicker and smaller oil spills are easier to handle than those with larger and more spreading area mechanically.

In general, booms have four following basic characteristics (ITOPF-a, 2004). A freeboard to contain the oil and to prevent or reduce oil to splash over the top of the boom. A flotation device, normally by air or made by buoyant materials. A below-water skirt to prevent or reduce oil loss under the boom. A longitudinal support, usually a chain or cable to strengthen the boom against wind, wave and current. This also serves as a weight or ballast to keep the boom upright in the water.

Booms can be classified by their area of use, purpose, or construction (Davitsales Inc, 2006). There are two major types of booming, classified according to its construction, namely; curtain booms, fence booms. According to Smith (1983), a fence boom is used as a vertical screen against the oil slick on the surface of water and is made of semi-rigid and rigid materials such as timbers. It is kept afloat by a plastic filled buoyancy compartment. A screen, extending below the surface of the surface water, prevents spilt oil from going through beneath the boom. The screen is ballasted by weights attached to its base. A curtain boom is made of long and continuous buoyancy tubes carrying a pendant skirt with chains of metal weights attached to the base. However, apart from these two types of booming above, there are also shore sealing booms and fire-resistant booms (Venticos *et al.*, 2004). Shore sealing booms are used as a barrier in intertidal zones, and fire-resistant booms are employed together with in-situ burning techniques.

1.3.1.2 Skimming

Another type of mechanical/physical method is skimming. However, different from booms, skimmers are designed to recover oil from the surface of water. There are different skimming techniques such as weir skimmer, oleophilic skimmer and suction skimmer (USEPA-b, 2004). Usually, the characteristics of this skimming equipment are as follows (USEPA-b, 2004):

Weir skimmers employ a weir to catch the oil on the water's surface. The oil will spill over a weir and into a skimmer, attaching with as little water as possible. The trapped oil/water mixture is then pumped or sucked from the skimmer to a storage tank for recycling or disposal.

Suction skimmers are similar to weir skimmers and float on the water, but use an external pump system. Oil is pumped out from the skimmer through wide floating heads to storage tanks. Both weir and suction skimmers face a problem of getting jammed and clogged by floating debris.

Oleophilic skimmers have a surface in different forms such as belts, disks, or continuous mop chains of oleophilic materials to catch the oil. The collected oil is removed from the sorbent surface by scraping off into a storage tank. This kind of skimmer can work fairly well with any spill of different thickness and in some different environmental conditions.

Under feasible conditions, these techniques are more preferable than the others since spilt oil removed from the environment can be collected and recycled properly (USCG, 2004). Thus, the use of booms and skimmers is still a primary option for combating marine oil spills (Mullin and Champ, 2003) since it is fairly quick and easy. More importantly, using booms and skimmers creates little direct further environmental impacts since it is merely a mechanical and physical method. However, both booms and skimmers are only effective in smooth water, but not at open sea as they can be considerably limited by several environmental factors such as wind, waves and currents (Fang and Johnston, 2001; ITOPF-a, 2004). At sea, a removal is around 15% or less for large oil spills (ITOPF-a, 2004). This mechanical/physical method is also complex, expensive and labour extensive (Mullin and Champ, 2003).

1.3.1.3 Sorbing materials

Sorbents are used together with other mechanical methods such as skimmers to recover and clean up oil spills by the adsorption (or/and) absorption of the oil. Sorbing materials in use today can generally be divided into three classes; namely natural inorganic products, natural organic products, and synthetic products (Choi and Cloud, 1992; Adebajo *et al.*, 2003; Bayat *et al.*, 2005; Ventikos *et al.*, 2004).

(i) Natural inorganic products

Natural inorganic products include perlite (Teas *et al.*, 2001; Roulia *et al.*, 2003), vermiculites (Hitzman and Okia, 1968), clays (Alther, 2001; Sayed *et al.*, 2003). By using the clay called Aswantly (Sayed *et al.*, 2003), the oil removal is quite encouraging and ranges from 63% to 100% for individual compositions, such as α SiO_2-Quart, $Na_2Si_2O_5(OH)_4$, $CaCO_3$, $MgCO_3$, $BaCO_3$, CaO, MgO and Fe_2O_3 of the clay and their mixture with the clay itself. Other natural mineral materials such as zeolites, graphite, diatomite, silica and even volcanic ash have also been reported to use in oil spill remediation (Adebajo *et al.*, 2003; Bayat *et al.*, 2005).

These products are used in the oil spill cleanup in the light of the fact that they are in-expensive and available in large quantities, however, one of their advantages is that they have a low sorption capacity for non-polar hydrocarbons (Ribeiro *et al.*, 2000).

(ii) Natural organic products

Natural organic products may fall into animal products and vegetable products (Deschamps *et al.*, 2003). **Animal products** used in oil spill remediation include wool (Johnson *et al.*, 1973; Choi and Moreau, 1993; Choi, 1996) and even feathers (Smith, 1983; Coxeter, 1994). A recycled wool based non-woven (77% wool/22% polyester) was tested in oil removal from water (Radetic *et al.*, 2003). In this study, the oil sorption ratio (oil/sorbent) ranging from 12 to 14 was recorded for the seawater containing 30g contaminant/500 ml seawater for both diesel and crude oil. Ironically, feathers have also been suggested to use as a sorbent for oil spills (Smith, 1983; Coxeter, 1994). Specifically, it was reported that chicken feathers, which are enclosed in nylon mesh to act as a type of “quilt”, could absorb fourteen times their own weight in oil (Coxeter, 1994), and the “quilt” can be used for three times before disposal by burning or in a landfill.

Another type of natural organic product that has been used extensively in oil spill remediation is a variety of **vegetable products**. These include cotton (Johnson *et al.*, 1973; Smith, 1983; Choi and Cloud, 1992; Choi and Moreau, 1993; Choi, 1996), wood (Smith, 1983), straw (Johnson *et al.*, 1973; Smith, 1983; Sun *et al.*, 2002), kapok (Choi and Moreau, 1993; Choi, 1996; Hori *et al.*, 2000); bark (Haussard *et al.*, 2003; Saito *et al.*, 2003), kenaf (Choi and Cloud, 1992; Choi, 1996); milk weed (Choi and Cloud, 1992; Choi and Moreau, 1993; Choi, 1996). A commercial cellulosic fiber from processed wood is also reported to use in the removal of oil (Teas *et al.*, 2001). In that study, a cellulosic fiber was found to be more effective in the removal of heavy crude oil from an artificial seawater bath than the others sorbents such as expanded perlite, and polypropylene. Recycled rubber has also been trialled in oil spill remediation (Aisien *et al.*, 2003). Another sorbent containing a mixture of raw peanut hut and kernel was also experimented (Solis, 2002). This mixture has to go through several basic treatment steps, including toasting in a rotary kiln at 310^{o}C to provide oil affinity. The heat-treated composition shows an achievement of 80% in oil removal (Solis, 2002). Recently, workers from Finland (Suni *et al.*, 2004) have reported the use of cotton grass fibre, a by-product of peat excavation, in sorbing oil spills. The cleaning efficiency is considerably high, up to 99%, and more importantly the sorbent is biodegradable, enabling it to be disposed of easily.

Although natural organic products have been used quite extensively in oil spill remediation thanks to their affordable production price and high sorption capacities for non-polar organic oils (Ribeiro *et al.*, 2000), they still have some disadvantages such as poor floating characteristics, relatively low sorption capacity and low hydrophobic (Choi and Cloud, 1992; Adebajo *et al.*, 2003).

(iii) Synthetic organic products

These materials employed in oil remediation include polymeric materials such as polyethylene or polyurethane (Teas *et al.*, 2001, Duong and Burford, 2006), polypropylene (Wei *et al.*, 2003) and glass wool (Smith, 1983). These sorbents have some advantages such as are fairly efficient, low density, low water uptake and excellent physical and chemical resistance (Wei *et al.*, 2003), however, their non-biodegradability is a major disadvantage (Choi and Cloud, 1992; Deschamps *et al.*, 2003).

One of the properties of sorbents is that they must have affinity for oil but not for water and float on water. They can be sprayed directly onto oil spills by helicopters or vessels. Using sorbents in oil spill remediation has proven to be effective. Since the performance is quick and the amount of oil collected is very high compared to the weight of sorbent and normally the oil: sorbent ratio is around from 8 to 30. However, the method is not suitable for dealing with large oil spills at open sea (Smith, 1983) due to the fact that under such conditions, the oil spill will be spread quickly by wind, waves and currents so that it is difficult for removing the oil from water by using this method. Another problem is incomplete sorption of the spilt oil. An oil spill, especially crude oil, consists of varying mixtures of hydrocarbons and some types of sorbents can strip only the lighter fractions, leaving the heavier components unstripped (Smith, 1983). Moreover, disposal and recovery of the absorbing materials is also a factor to consider (Mullin and Champ, 2003). This is the case when using hay or straw, which have a high material-to-oil sorption ratio (De Lew, 1965; Bunn, 1970; Jacobs, 1974; Flaherty, 1989). Moreover, some of sorbing materials such as polypropylene are quite expensive (Christodoulou, 2002). It is also noted that the employment of a sorbent is always accompanied by a suitable mechanical device, such as skimmers to collect and dispose the oiled sorbent off.

1.3.2 Chemical treatment of oil spills

Chemical methods are very popular and make a considerable contribution to oil spill treatment and remediation (Smith, 1983). Various chemicals are used but they may be categorized into several major groups (Ventikos *et al.*, 2004): dispersing agents, sinking agents (sand, brick-dust or even cement) and others (gelling agents, emulsion breakers). However, dispersants are used more commonly.

1.3.2.1 Dispersing materials

Dispersants have been widely employed in combating oil spills since they can treat large oil slicks in a comparatively short time (Flaherty, 1989). Dispersants, a group of chemicals, are used to accelerate the process of natural dispersion of oil spills, and can be sprayed onto them from airplanes, helicopters or vessels. Various dispersants have been used in the battle against oil spills. According to ITOPF-b (2004), there are three main types of dispersants. The first type is hydrocarbon solvent-based dispersants, containing 15-25% surfactant. This dispersant becomes ineffective when pre-diluted with seawater therefore it needs to spray neat onto the spill. Dose rates of this dispersant-to-oil are 1:1 and 1:3. The second type is dilutable concentrate dispersants with a higher surfactant concentration. The third is similar to the second type in term of formulation, however, is designed to be spray undiluted, with a typical dose rate of dispersant-to-oil ranging from 1:5 to 1:30. As the last two dispersant types have a higher surfactant concentration and require a lower dispersant-to-oil ratio, they are more favourably employed in the treatment of spills.

Some examples of using dispersants in oil spill remediation are the use of water based non-ionic polymeric surfactants (Al-Sabagh and Atta, 1999), and distiller's dried grain (DDG), such as wheat, corn (Working *et al.,* 1999). It is reported that the non-ionic polymeric surfactants have a dispersion efficiency of 100% and the DDG can offer a removal ranging from 30 to 90%. The DDG is also tested on the cleaning of oil from wildlife.

Dispersants are found to be effective in both sea and fresh water environment, especially when used near the source of an oil spill - before it gets weathered and mixed with water (Flaherty, 1989). This is due to the fact that as oil becomes weathered, it increases in viscosity and forms water-in-oil emulsion (called "mousse") and this substance is very difficult to disperse. Dispersants break spilt oil into small particles of different sizes (IPIECA, 2001) that can be easier for bacteria to degrade. As can be sprayed from aircraft, dispersants are able to treat large areas compared to other methods. One example of that was the use of dispersant in the Sea Empress incident where at least 18,000 tonnes of crude oil could be removed (White, 2000). They can also be applicable in rough seawater where the implementation of physical and mechanical methods such as booming and skimming becomes very difficult (USEPA-c, 2004). Moreover, as dispersed oil is not affected by wind, it is less likely for an oil spill to reach shorelines or any vulnerable area located downwind of the oil spill (USEPA-c, 2004). Danger to wildlife, such as birds, is considerably reduced as the floating oil spill is removed by dispersants. Moreover, using dispersants in oil spill remediation does not create any wastage (NOAA-b, 2004).

However, the dispersion of an oil spill is not actually oil removal since it only breaks the oil up into finer particles, resulting in an increase in oil concentration in water around the oil spill considerably (IPIECA, 2001; Christodoulou, 2002). This may pollute the water and have negative impacts on flora and fauna. Also dispersants are likely to be ineffective in handling high viscosity oils (SLRER, 2002). However, in some cases due to the excess use of dispersants, the secondary effects on water quality and ecosystems can be generated (Christodoulou, 2002). The application scope of this method is limited since it is only applicable in water bodies with enough depth and volume for mixing and dilution (NOAA-a, 2004). This method is also under influence of water salinity and temperature (USEPA-c, 2004). It is found that when used in warm water or water with a normal salinity level dispersants offer better outcome.

1.3.2.2 Sinking materials

Oil spills are also treated using sinking agents. Typical sinking agents include sand, brick-dust, fly ash, china clay, volcanic ash, coal dust, stucco, slaked lime, spent tannery lime, crush stone and cement (Dewling, 1980; Smith, 1983). Some others such as barite treated with latex and asbestos (treated 100% hydrophobic) were used as sinking agents (Liu and Liptak, 1997). A sinking agent is either in a powdered or granulated form of high density. When sprayed over an oil spill, it will absorb and adhere firmly to the oil and the combination of oil and sinking materials will become heavy enough to sink.

However, the use of sinking agents has also some problems. Firstly, many sinking materials do not keep the oil permanently immobile and release of the oil, causing re-pollution after some time. Sinking agents are also not applicable in enclosed water or shallow water (less than 100m deep), in which the volume of water is not sufficient to prevent the oil particles from reforming an oil slick again. In addition, oil that sinks to the bottom contaminates benthic life and degrades more slowly than when they are floated, dispersed, or dissolved in water (NRC, 1989). It is also a challenge when applying light powdery materials in open-sea, or under windy conditions. Sinking of oil spills, as it name suggests, actually does not remove oil spills, therefore, this method is now not permitted to use in the United States (JPL, 2004).

1.3.2.3 Others

Other chemical materials have also used in the combat against oil spills with a less extensive scale. They include emulsion breaker (Buist *et al.*, 1999; Nordvik *et al.* 1996), and gelling agents or know as solidifiers (Delaune *et al.*, 1999; Reynolds *et al.*, 2001; USEPA-f, 2004), neutralizing agents (Ventikos *et al.*, 2004).

1.3.3. Bioremediation of oil spills

Bioremediation of oil spills is the process of using living organisms to degrade pollutants and recover environmental quality (Atlas and Cerniglia, 1995). In recent years, biological techniques have been used extensively. This method has an advantage of generating no further negative environmental impact (Wood *et al.*, 1997), uses natural processes, transforms contaminants instead of simply moving them from one media to another and is affordable (Senn, 1999). Much research regarding biological treatment of oil spills has been done, including microbial surfactants (Harvey *et al.*, 1990), bacterial consortia (Chhatre *et al.*, 1996) and marine microbial mats (Cohen, 2002). Bioremediation of oil spills and petroleum contaminants have also been investigated by Atlas and Cerniglia (1995), Prince (1997), Head and Swannell (1999); Tsutsumi *et al.* (2000). In particular, biological treatment of oil spills in cold environments has also been studied (Margesin and Schinner, 1999). In addition, chicken droppings have also been documented in removing oil from soil as they contain micro-organisms capable of degrading crude oil (Ijah and Antai, 2003).

However, biological treatment is not very effective, especially with some sorts of recalcitrant oil containing hydrocarbons that cannot be biodegraded (Atlas and Cerniglia, 1995). For example, some components found in petroleum like polynuclear aromatics and aliphatic hydrocarbons that are not bio-available, as a result, are not biodegraded. Moreover, bioremediation is ineffective in removing oil spills that consist of large coherent masses and for sunken oil spills (Smith, 1983). This is due to the fact that biodegradation is active on the surface layer of the oil spill so that it cannot work effectively in the sunken oil or a large coherent mass, and the growth of oil degrader only takes place at the oil-water interface. Bioremediation is also limited by abiotic environmental factors such as a low level of nutrients including phosphate and fixed forms of nitrogen, very low temperature and insufficient oxygen (Atlas and Cerniglia, 1995).

These factors are very important for micro-organisms to degrade oil spills, and low levels of nutrients, very low temperature and insufficient oxygen will not only slower degradation rates but also retard microbiological growth. Bioremediation is also time consuming (USEPA-d, 2004) since the rate is normally equal to the half-lives of hydrocarbons (Wang *et al.*, 2001), as a result, it is unlikely to prevent the vast majority of an oil spill spreading to shorelines (ITOPF-e, 2004). This method is also not recommended to use at sea environment as any material added can be diluted and lost from the spill (ITOPF-e, 2004).

1.3.4 In-situ burning of oil spills

Oil spills are also treated by burning-off (Mullin and Champ, 2003). Ignition of an oil spill can be done in many ways, using various devices such as a diesel-soaked rag to more modern and sophisticated equipment like Helitorch, a sort of flame-thrower suspended beneath a helicopter (NOAA, 1997; USEPA-e, 2004; ITOPF-e, 2004). When an oil spill is fired, it burns off quickly and fiercely as it covers a large area due to oil's properties of flammability. Under favourable conditions, this method is efficient, fast and a relatively simple way for oil spill removal. Burning is not very costly and only required a minimal investment of equipment and manpower to deal with (NOAA, 1997). This method also reduces storage and disposal requirements, as it does not have oil to be collected and create a smaller amount of residues. Burning is also very versatile and can be conducted on open water, on rivers, on wetlands and marshes as well as dry lands. Therefore, in some circumstances such as oil spills in icy water or in a marsh, burning can be the only option to response (NOAA, 1997).

However, burning oil is not an environmentally friendly method as it causes air pollution and leaves residual unburnt particles (Smith, 1983; Christodoulou, 2002). This is due to the fact that oil spreads out over the water's surface to form a thin layer and the lower part of this layer is cooled by water. When the oil is burnt the lighter layer on top is burned off rapidly but the layer at the bottom is left unburnt. Burning is also not workable if a spill is thinner than 1-2 mm (NOAA, 1997) due to heat loss to water and insufficient vapours. It is also limited by several environmental factors such as waves, wind and current. As for some kinds of emulsified oil, especially those with water content above 25%, burning can be very difficult as most slicks are un-ignitable (Buist *et al.*, 1999). Moreover, it can pose a fire threat to the coastal area close to the fire especially in case of wind change (Jacobs, 1974). Burning can also be dangerous for the personnel conducting operations (Buist *et al.*, 1999).

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Appendix 2

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Table 1: Viscosity values of the contaminants, measured by using a capillary viscometer tube (Ostwald's method).

Contaminant	1st reading	2nd reading	3rd reading	Average value (cSt)
Arab medium crude oil (AO)	50.3508	49.8476		**50.10**
Engine oil (EO)	307.82	306.44		**307.13**
Gippsland crude oil (GO)	1.43	1.40	1.43	**1.42**
Merinie crude oil (MO)	4.16	4.16	4.08	**4.13**

Table 2: Experimental data and statistical analysis for the pick-up of Arab medium oil (AO) from a petri dish using the optimal iron powder grade, MH300.29. Experiments were conducted in five replicates.

Average R	P%(mean)	s	%CV	SE	95%
1.04	40.84	3.52	8.61	1.57	4.37
1.96	60.90	3.26	5.35	1.46	4.04
3.07	83.40	3.29	3.95	1.47	4.09
4.04	93.00	1.78	1.91	0.80	2.21
6.10	98.00	0.99	1.01	0.44	1.23
8.02	98.77	0.41	0.41	0.18	0.51
10.07	99.30	0.13	0.13	0.06	0.17
11.99	99.85	0.28	0.28	0.12	0.34
14.03	100.00	0.13	0.13	0.06	0.16

Table 3: Experimental data and statistical analysis for the pick-up of Arab medium oil (AO) from duck feathers using the coarse spongy annealed grade, M40. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	s	%CV	SE	95%
1	88.33	90.24	86.77	85.05	78.43	85.76	1.01	1.14	0.45	1.26
2	90.17	94.74	90.30	92.93	91.86	92.00	3.10	3.33	1.38	3.84
3	91.65	96.15	94.31	95.60	96.04	94.75	0.96	0.98	0.43	1.19
4	96.57	96.68	96.30	96.63	96.98	96.63	0.54	0.54	0.24	0.66
5	97.18	98.22	97.37	96.45	97.69	97.38	0.41	0.42	0.18	0.51
6	97.36	98.29	97.98	97.62	97.86	97.82	0.36	0.36	0.16	0.45
7	98.03	98.69	98.35	97.76	98.21	98.21	0.07	0.07	0.03	0.08
8	98.43	98.72	98.52	98.06	98.35	98.42	0.08	0.08	0.04	0.10
9	98.95	99.05	98.96	99.08	98.77	98.97	0.06	0.06	0.03	0.07

Table 4: Gippsland crude oil (GO) pickup from plumage using the optimal iron powder grade, MH300.29. Experiments were conducted in five replicates.

N	Five replicates (%)					C%(mean)	s	%CV	st error	95%
1	42.07	40.87	36.49	41.13	46.30	41.37	3.50	8.45	1.56	4.34
2	62.79	52.74	64.39	62.88	67.02	61.96	5.43	8.77	2.43	6.74
3	75.90	66.89	74.39	69.50	78.01	72.94	4.61	6.32	2.06	5.72
4	81.82	75.80	80.70	79.20	84.99	80.50	3.38	4.20	1.51	4.20
5	85.84	84.47	85.79	85.34	88.58	86.01	1.54	1.79	0.69	1.91
6	89.01	88.81	89.82	89.36	92.18	89.84	1.36	1.52	0.61	1.69
7	92.18	92.69	92.28	92.43	95.98	93.11	1.62	1.74	0.72	2.01
8	95.56	94.98	94.21	94.33	96.83	95.18	1.07	1.12	0.48	1.33
9	96.62	97.03	95.79	96.45	97.89	96.76	0.77	0.80	0.35	0.96
10	97.25	97.95	96.67	97.40	98.73	97.60	0.78	0.80	0.35	0.97

Table 5: Comparison of the pick-up of Gippsland crude oil (GO), using the optimal iron powder grade, MH300.29, between duck and penguin feathers. Experiments were conducted in five replicates.

N	Duck feathers		Penguin feathers	
	F (%)	95%	F (%)	95%
1	98.78	1.31	98.12	0.16
2	99.85	0.40	98.54	0.10
3	100.08	0.22	98.84	0.18
4	100.21	0.26	99.03	0.12
5	100.19	0.22	99.11	0.20
6	100.15	0.22	99.12	0.12
7	100.20	0.15	99.16	0.11

Sample Calculation 1: Calculation of the Percentage by Weight of Oil Pick-up from a petri dish by iron powder

Weight of petri dish, w_1 = 47.1921 g

Weight of petri dish + oil, w_2 = 47.3721 g

Weight of petri dish + oil + iron powder, w_3 = 47.4615 g

Weight of petri dish + remaining oil left on petri dish, w_4 = 47.2662 g

Using equation (2.1) the particle-to-chemical ratio, R, is calculated as:

$R = (w_3 - w_2) / (w_2 - w_1)$

$= (47.4615 - 47.3721) / (47.3721 - 47.1921)$

$= 0.996$

Using equation (2.2) the percentage by weight P (%) of oil picked up is calculated as:

$P (\%) = [(w_2 - w_4) / (w_2 - w_1)] \times 100$

(2.2)

$= [(47.3721 - 47.2662) / (47.3721 - 47.1921)] \times 100$

$= 45.11\%$

Sample Calculation 2: Calculation of the Percentage by Weight of Oil Pick-up from feathers by iron powder

Mass of feathers, f_1	= 0.0694 g
Mass of oil-laden feathers, f_2	= 0.7037 g
Mass of remaining oil residual in petri dish, ϕ	= 0.0211 g
Mass of oil-laden feathers removed from petri dish, f_3;	$f_3 = f_2 - \phi$
	= 0.7037 g - 0.0211 g
	= 0.6826 g

For example, at the maximum value of N, corresponding to the maximum value of F, the mass of treated feathers, f_4 = 0.0710 g

Percentage of oil removed, F (%) = $(f_3 - f_4)/(f_3 - f_1) \times 100$ = (0.6826 - 0.0710)/(0.7037 - 0.0694) × 100 = 99.74%

Error Analysis Using the Two-tailed Student t-distribution for 95% Confidence Limits.

The standard deviation, *s*, is given by equation A.2.1

$$s = \left(\frac{\sum \left(x_i - \bar{x} \right)^2}{n-1} \right)^{\frac{1}{2}}$$

(A.2.1)

where x_i is the initial value for x, $\bar{x}$ is the mean of the sample and n is the number of replicates. The 95% confidence interval was calculated using equation A.2.2

$$\bar{x} \pm t_c \sigma_{\bar{x}}$$

(A.2.2)

where standard error $\sigma_{\bar{x}} = \frac{s}{\sqrt{n}}$, and the t_c is the 95% confidence value in a standard t distribution table (Kirkup, 1994).

Appendix 3.1

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE : Standard error
95%: 95% interval confidence

Table 1: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the coarse atomised un-annealed grade-A40S. Experiments were conducted in five replicates.

R mean	P mean (%)	S	%CV	SE	95%
1.03	28.11	0.75	2.68	0.34	0.94
2.05	46.60	2.24	4.81	1.00	2.78
3.03	65.33	1.82	2.78	0.81	2.26
4.09	76.43	3.37	4.41	1.51	4.19
5.94	85.80	1.87	2.18	0.84	2.33
8.08	89.30	1.19	1.34	0.53	1.48
10.04	91.00	1.23	1.35	0.55	1.52
11.98	92.40	0.78	0.84	0.35	0.96
13.92	92.57	1.15	1.25	0.52	1.43
16.02	92.98	0.64	0.68	0.28	0.79
17.98	93.30	0.38	0.40	0.17	0.47

Table 2: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the coarse spongy un-annealed grade-M40. Experiments were conducted in five replicates.

R	P mean (%)	S	%CV	SE	95%
1.09	36.35	2.077	5.71	0.93	2.58
2.03	68.68	1.415	2.06	0.63	1.76
3.07	82.47	2.099	2.55	0.94	2.61
4.01	87.80	1.230	1.40	0.55	1.53
6.08	92.80	0.412	0.44	0.18	0.51
8.09	95.58	0.924	0.97	0.41	1.15
10.15	97.50	0.601	0.62	0.27	0.75
12.01	98.70	0.292	0.30	0.13	0.36
14.05	99.32	0.721	0.73	0.32	0.90
16.05	99.46	0.190	0.19	0.09	0.24
17.95	99.64	0.229	0.23	0.10	0.28

Table 3: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the fine atomised un-annealed grade-A100S. Experiments were conducted in five replicates.

Average R	P%(mean)	S	%CV	SE	95%
1.08	36.72	1.05	2.86	0.47	1.30
2.05	50.80	2.88	5.67	1.29	3.57
3.04	66.00	3.83	5.80	1.71	4.75
4.02	78.50	3.27	4.17	1.46	4.06
6.00	91.89	1.29	1.41	0.58	1.60
8.09	96.45	0.52	0.54	0.23	0.64
10.00	97.80	0.51	0.52	0.23	0.64
12.08	98.81	0.18	0.18	0.08	0.22
13.97	98.99	0.14	0.14	0.06	0.17
15.98	99.09	0.27	0.28	0.12	0.34

Table 4: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the fine spongy un-annealed grade-C100.29. Experiments were conducted in five replicates.

Average R	P%(mean)	S	%CV	SE	95%
1.08	40.53	1.46	3.59	0.65	1.81
2.01	65.58	3.01	4.59	1.35	3.74
3.08	85.40	1.27	1.49	0.57	1.58
4.05	92.70	0.86	0.92	0.38	1.06
6.03	97.60	0.83	0.85	0.37	1.03
7.95	99.00	0.16	0.16	0.07	0.20
10.08	99.31	0.36	0.36	0.16	0.44
12.01	99.45	0.15	0.15	0.07	0.18
14.02	99.64	0.20	0.20	0.09	0.25
16.06	99.75	0.21	0.21	0.10	0.26

Table 5: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the fine atomised annealed grade-ASC100.29. Experiments were conducted in five replicates.

Average R	P%(mean)	S	%CV	SE	95%
1.07	31.81	1.38	4.35	0.62	1.72
1.94	49.71	2.90	5.84	1.30	3.60
3.02	75.30	1.11	1.47	0.49	1.37
4.01	87.60	1.02	1.17	0.46	1.27
6.06	93.53	1.11	1.19	0.50	1.38
8.05	95.72	0.57	0.59	0.25	0.71
10.03	96.76	0.58	0.59	0.26	0.71
12.08	97.71	0.15	0.15	0.07	0.19
14.17	98.59	0.10	0.10	0.04	0.12
16.02	98.96	0.23	0.24	0.10	0.29

Table 6: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the fine spongy annealed grade-NC100.24. Experiments were conducted in five replicates.

Average R	P%(mean)	S	%CV	SE	95%
1.01	39.84	3.70	9.29	1.65	4.59
2.03	70.90	1.59	2.25	0.71	1.98
3.02	88.00	0.48	0.54	0.21	0.60
3.93	92.06	1.25	1.35	0.56	1.55
6.07	95.70	0.76	0.80	0.34	0.95
8.07	97.50	0.80	0.82	0.36	1.00
10.07	98.70	0.51	0.52	0.23	0.63
12.09	99.11	0.35	0.35	0.16	0.43
13.95	99.27	0.24	0.25	0.11	0.30
15.98	99.47	0.71	0.71	0.32	0.88

Table 7: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the superfine atomised annealed grade-ASC300. Experiments were conducted in five replicates.

Average R	P%(mean)	S	%CV	SE	95%
1.07	39.75	2.36	5.93	1.05	2.93
1.88	56.10	2.61	4.65	1.17	3.24
3.06	80.00	2.49	3.11	1.11	3.09
4.02	90.63	2.20	2.43	0.99	2.74
6.06	95.86	1.20	1.25	0.54	1.49
8.07	98.06	0.24	0.25	0.11	0.30
10.05	98.49	0.77	0.78	0.34	0.96
12.09	99.19	0.16	0.17	0.07	0.20
14.05	99.32	0.12	0.12	0.05	0.15

Table 8: Experimental data and statistical analysis for the pick-up of Arab medium crude oil (AO) from a petri dish using the superfine spongy annealed grade-MH300.29. Experiments were conducted in five replicates.

Average R	P%(mean)	S	%CV	SE	95%
1.04	40.84	3.52	8.61	1.57	4.37
1.96	60.90	3.26	5.35	1.46	4.04
3.07	83.40	3.29	3.95	1.47	4.09
4.04	93.00	1.78	1.91	0.80	2.21
6.10	98.00	0.99	1.01	0.44	1.23
8.02	98.77	0.41	0.41	0.18	0.51
10.07	99.30	0.13	0.13	0.06	0.17
11.99	99.85	0.28	0.28	0.12	0.34
14.03	100.00	0.13	0.13	0.06	0.16

Table 9: Comparison of oil pick-up, P (%), from a petri dish amongst 4 different atomised grades.The individual profiles for each grade are presented in Tables 1, 3, 5 and 7. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

Coarse atomised un-annealed grade, A40S			**Fine atomised un-annealed grade, A100S**			**Fine atomised annealed grade, ASC100.29**			**Superfine atomised annealed grade, ASC300**		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**	**R**	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	28.11	0.34	1	36.72	0.47	1	31.81	0.62	1	39.75	1.05
2	46.60	1.00	2	50.80	1.29	2	49.71	1.30	2	56.10	1.17
3	65.33	0.81	3	66.00	1.71	3	75.30	0.49	3	80.00	1.11
4	76.43	1.51	4	78.50	1.46	4	87.60	0.46	4	90.63	0.99
6	85.80	0.84	6	91.89	0.58	6	93.53	0.50	6	95.86	0.54
8	89.30	0.53	8	96.45	0.23	8	95.72	0.25	8	98.06	0.11
10	91.00	0.55	10	97.80	0.23	10	96.76	0.26	10	98.49	0.34
12	92.40	0.35	12	98.81	0.08	12	97.71	0.07	12	99.19	0.07
14	92.57	0.52	14	98.99	0.06	14	98.59	0.04	**14**	**99.32**	0.05
16	92.98	0.28	**16**	**99.09**	0.12	**16**	**98.96**	0.10			
18	**93.30**	0.17									

Table 10: Comparison of oil pick-up, P (%), from a petri dish amongst 4 different spongy grades. The individual profiles for each grade are presented in Tables 2, 4, 6 and 8. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

Coarse spongy un-annealed grade, M40			**Fine spongy un-annealed grade, C100.29**			**Fine spongy annealed grade, NC100.24**			**Superfine spongy annealed grade, MH300.29**		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**	**R**	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	36.35	0.93	1	40.53	0.65	1	39.84	1.65	1	40.84	1.57
2	68.68	0.63	2	65.58	1.35	2	70.90	0.71	2	60.90	1.46
3	82.47	0.94	3	85.40	0.57	3	88.00	0.21	3	83.40	1.47
4	87.80	0.55	4	92.70	0.38	4	92.06	0.56	4	93.00	0.80
6	92.80	0.18	6	97.60	0.37	6	95.70	0.34	6	98.00	0.44
8	95.58	0.41	8	99.00	0.07	8	97.50	0.36	8	98.77	0.18
10	97.50	0.27	10	99.31	0.16	10	98.70	0.23	10	99.30	0.06
12	98.70	0.13	12	99.45	0.07	12	99.11	0.16	12	99.85	0.12
14	99.12	0.32	14	99.64	0.09	14	99.27	0.11	**14**	**100.00**	0.06
16	99.26	0.09	**16**	**99.75**	0.10	**16**	**99.47**	0.32			
18	**99.34**	0.10									

Table 11: Particle size of grades and their maximum oil removal, P_o (%), from a petri dish

N	**Grade**	**Particle size distribution (micron)**	**P_o(%)**	**R_o**
1	A40S	274	93.3	18

2	M40S	185	99.64	18
3	A100S	80	99.09	16
4	ASC100.29	93	98.96	16
5	C100.29	89	99.75	16
6	NC100.24	100	99.47	16
7	ASC300	36	99.32	14
8	MH300.29	37	99.99	14

Table 12: Comparison of oil pick-up, P (%), from a petri dish between atomised and spongy coarse grades. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

A40S- atomised coarse un-annealed			**M40- spongy coarse un-annealed**		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	28.11	0.34	1	36.35	0.93
2	46.60	1.00	2	68.68	0.63
3	65.33	0.81	3	82.47	0.94
4	76.43	1.51	4	87.80	0.55
6	85.80	0.84	6	92.80	0.18
8	89.30	0.53	8	95.58	0.41
10	91.00	0.55	10	97.50	0.27
12	92.40	0.35	12	98.70	0.13
14	92.57	0.52	14	99.12	0.32
16	92.98	0.28	16	99.26	0.09
18	**93.30**	0.17	**18**	**99.34**	0.10

Table 13: Comparison of oil pick-up, P (%), from a petri dish between atomised and spongy fine un-annealed grades. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

A100S- atomised fine un-annealed			**C100-29- spongy fine un-annealed**		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	36.72	0.47	1	40.53	0.65
2	50.80	1.29	2	65.58	1.35
3	66.00	1.71	3	85.40	0.57
4	78.50	1.46	4	92.70	0.38
6	91.89	0.58	6	97.60	0.37
8	96.45	0.23	8	99.00	0.07
10	97.80	0.23	10	99.31	0.16
12	98.81	0.08	12	99.45	0.07
14	98.99	0.06	14	99.64	0.09
16	**99.09**	0.12	**16**	**99.75**	0.10

Table 14: Comparison of oil pick-up, P (%), from a petri dish between atomised and spongy fine annealed grades. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

ASC100.29- atomised fine annealed			NC100.24- spongy fine annealed		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	31.81	0.62	1	39.84	1.65
2	49.71	1.30	2	70.90	0.71
3	75.30	0.49	3	88.00	0.21
4	87.60	0.46	4	92.06	0.56
6	93.53	0.50	6	95.70	0.34
8	95.72	0.25	8	97.50	0.36
10	96.76	0.26	10	98.70	0.23
12	97.71	0.07	12	99.11	0.16
14	98.59	0.04	14	99.27	0.11
16	**98.96**	0.10	**16**	**99.47**	0.32

Table 15: Comparison of oil pick-up, P (%), from a petri dish between atomised and spongy superfine annealed grades. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

ASC300- superfine atomised annealed			MH300.29 superfine spongy annealed		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	39.75	1.05	1	40.84	1.57
2	56.10	1.17	2	60.90	1.46
3	80.00	1.11	3	83.40	1.47
4	90.63	0.99	4	93.00	0.80
6	95.86	0.54	6	98.00	0.44
8	98.06	0.11	8	98.77	0.18
10	98.49	0.34	10	99.30	0.06
12	99.19	0.07	12	99.85	0.12
14	**99.32**	0.05	**14**	**100.00**	0.06

Table 16: Comparison of oil pick-up, P (%), from a petri dish between annealed and un-annealed spongy grades. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

C100-29- un-annealed fine spongy			NC100.24- annealed fine spongy		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	40.53	0.65	1	39.84	1.65
2	65.58	1.35	2	70.90	0.71
3	85.40	0.57	3	88.00	0.21
4	92.70	0.38	4	92.06	0.56
6	97.60	0.37	6	95.70	0.34
8	99.00	0.07	8	97.50	0.36
10	99.31	0.16	10	98.70	0.23
12	99.45	0.07	12	99.11	0.16
14	99.64	0.09	14	99.27	0.11
16	**99.75**	0.10	**16**	**99.47**	0.32

Table 17: Comparison of oil pick-up, P (%), from a petri dish between annealed and un-annealed atomised grades. Experiments were conducted in five replicates. The bold figures are R_o and P_o.

A100S- un-annealed fine atomised			ASC100.29- annealed fine atomised		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**
1	36.72	0.47	1	31.81	0.62
2	50.80	1.29	2	49.71	1.30
3	66.00	1.71	3	75.30	0.49
4	78.50	1.46	4	87.60	0.46
6	91.89	0.58	6	93.53	0.50
8	96.45	0.23	8	95.72	0.25
10	97.80	0.23	10	96.76	0.26
12	98.81	0.08	12	97.71	0.07
14	98.99	0.06	14	98.59	0.04
16	99.09	0.12	16	98.96	0.10

Appendix 3.2

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Table 1: Experimental data and statistical analysis for the pick-up, F (%) of Arab medium crude oil (AO) from duck feathers using the coarse atomised un-annealed grade-A40S. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	68.36	66.91	74.47	70.39	74.73	70.97	3.54	4.98	1.58	4.39
2	79.64	83.55	86.66	79.33	86.39	83.11	3.53	4.25	1.58	4.39
3	87.26	87.47	92.51	82.82	89.50	87.91	3.54	4.03	1.58	4.40
4	87.38	92.84	95.42	86.80	92.72	91.03	3.76	4.13	1.68	4.67
5	91.67	95.55	97.09	90.51	95.58	94.08	2.83	3.01	1.27	3.51
6	94.46	96.81	97.46	92.31	96.85	95.58	2.16	2.26	0.97	2.68
7	96.23	97.58	97.63	95.99	97.60	97.00	0.82	0.85	0.37	1.02
8	96.58	97.92	98.26	96.78	98.27	97.56	0.82	0.84	0.37	1.02
9	97.17	98.55	98.53	97.78	98.52	98.11	0.62	0.63	0.28	0.77

Table 2: Experimental data and statistical analysis for the pick-up, F (%) of Arab medium crude oil (AO) from duck feathers using the coarse spongy un-annealed grade-M40S. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	88.33	90.24	86.77	85.05	78.43	85.76	4.53	5.28	2.02	5.62
2	90.17	94.74	90.30	92.93	91.86	92.00	1.91	2.08	0.85	2.37
3	91.65	96.15	94.31	95.60	96.04	94.75	1.88	1.99	0.84	2.34
4	96.57	96.68	96.30	96.63	96.98	96.63	0.25	0.25	0.11	0.31
5	97.18	98.22	97.37	96.45	97.69	97.38	0.66	0.67	0.29	0.81
6	97.36	98.29	97.98	97.62	97.86	97.82	0.35	0.36	0.16	0.44
7	98.03	98.69	98.35	97.76	98.21	98.21	0.35	0.35	0.15	0.43
8	98.43	98.72	98.52	98.06	98.35	98.42	0.24	0.25	0.11	0.30
9	98.75	98.85	98.86	98.28	98.77	98.70	0.24	0.24	0.11	0.30

Table 3: Experimental data and statistical analysis for the pick-up, F (%) of Arab medium crude oil (AO) from duck feathers using the fine atomised un-annealed grade-A100S. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	88.48	88.43	84.77	79.08	82.86	84.72	3.97	4.69	1.78	4.93
2	93.00	95.75	94.02	89.68	90.36	92.56	2.53	2.73	1.13	3.14
3	93.55	96.11	95.85	93.77	95.05	94.87	1.17	1.24	0.52	1.46
4	95.17	96.56	97.82	96.48	96.18	96.44	0.95	0.99	0.42	1.18
5	96.34	97.10	98.12	96.72	97.86	97.23	0.75	0.77	0.34	0.93
6	96.70	97.38	98.34	97.33	98.58	97.67	0.78	0.80	0.35	0.96
7	97.13	97.71	98.56	98.46	98.76	98.12	0.68	0.70	0.31	0.85
8	98.55	98.08	98.78	98.58	98.84	98.56	0.30	0.30	0.13	0.37
9	98.66	98.49	98.87	98.87	98.91	98.76	0.18	0.18	0.08	0.22

Table 4: Experimental data and statistical analysis for the pick-up, F (%), of Arab medium crude oil (AO) from duck feathers using the fine spongy un-annealed grade-C100.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	85.75	90.26	92.00	90.05	92.94	90.20	2.76	3.06	1.24	3.43
2	88.09	92.71	95.34	91.36	93.59	92.22	2.72	2.95	1.22	3.38
3	92.95	95.25	96.21	95.40	96.24	95.21	1.34	1.41	0.60	1.67
4	95.77	96.68	97.54	98.26	98.17	97.28	1.06	1.09	0.47	1.31
5	97.51	97.20	98.47	98.45	98.46	98.02	0.61	0.63	0.27	0.76
6	97.57	97.84	98.71	98.93	98.63	98.34	0.59	0.60	0.27	0.74
7	98.23	98.13	98.80	99.20	98.69	98.61	0.44	0.44	0.19	0.54
8	98.77	98.89	98.92	99.46	98.86	98.98	0.28	0.28	0.12	0.34
9	99.16	99.07	99.13	99.52	99.22	99.22	0.18	0.18	0.08	0.22

Table 5: Experimental data and statistical analysis for the pick-up, F (%), of Arab medium crude oil (AO) from duck feathers using the fine atomised annealed grade-ASC100.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	89.21	90.43	88.20	89.56	87.95	89.07	1.01	1.14	0.45	1.26
2	94.16	92.96	97.69	91.21	89.55	93.11	3.10	3.33	1.38	3.84
3	96.42	97.98	98.79	96.74	97.32	97.45	0.96	0.98	0.43	1.19
4	98.77	98.57	98.90	97.75	97.84	98.37	0.54	0.54	0.24	0.66
5	98.91	98.79	98.96	98.36	97.99	98.60	0.41	0.42	0.18	0.51
6	98.95	99.05	99.12	98.73	98.23	98.82	0.36	0.36	0.16	0.45
7	99.08	99.11	99.16	99.06	98.98	99.08	0.07	0.07	0.03	0.08
8	99.00	99.20	99.18	99.11	99.06	99.11	0.08	0.08	0.04	0.10
9	99.04	99.16	99.14	99.06	99.04	99.09	0.06	0.06	0.03	0.07

Table 6: Experimental data and statistical analysis for the pick-up, F (%), of Arab medium crude oil (AO) from duck feathers using the fine spongy annealed grade-NC100.24. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	88.35	92.80	92.21	91.86	92.11	91.47	1.78	1.94	0.80	2.21
2	92.32	94.95	95.26	94.28	95.73	94.51	1.33	1.41	0.60	1.65
3	94.62	96.62	97.63	97.12	97.99	96.80	1.32	1.37	0.59	1.64
4	95.96	98.15	98.19	97.91	98.27	97.70	0.98	1.00	0.44	1.21
5	98.81	98.65	98.84	98.39	98.89	98.72	0.20	0.20	0.09	0.25
6	99.05	99.09	99.00	98.66	99.07	98.97	0.18	0.18	0.08	0.22
7	99.27	99.15	99.24	98.88	99.13	99.13	0.15	0.15	0.07	0.19
8	99.45	99.35	99.28	99.14	99.23	99.29	0.12	0.12	0.05	0.15
9	99.62	99.47	99.32	99.29	99.41	99.42	0.13	0.13	0.06	0.17

Table 7: Experimental data and statistical analysis for the pick-up, F (%), of Arab medium crude oil (AO) from duck feathers using the superfine atomised annealed grade-ASC300. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	88.81	92.08	90.11	93.88	91.96	91.37	1.95	2.14	0.87	2.43
2	94.26	93.30	93.80	96.53	94.30	94.44	1.24	1.31	0.55	1.54
3	96.65	98.23	96.38	97.86	97.02	97.23	0.79	0.81	0.35	0.98
4	97.61	98.97	97.62	99.22	98.71	98.43	0.76	0.77	0.34	0.94
5	98.19	99.15	98.33	99.32	99.10	98.82	0.52	0.52	0.23	0.64

6	99.03	99.30	99.39	99.70	99.36	99.36	0.24	0.24	0.11	0.29
7	99.29	99.34	99.43	99.68	99.68	99.48	0.19	0.19	0.08	0.23
8	99.45	99.52	99.52	99.70	99.63	99.57	0.10	0.10	0.04	0.12
9	99.52	99.48	99.59	99.72	99.65	99.59	0.09	0.09	0.04	0.12

Table 8: Experimental data and statistical analysis for the pick-up, F (%), of Arab medium crude oil (AO) from duck feathers using the superfine spongy annealed grade-MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	94.26	95.57	96.36	91.94	95.27	94.68	1.71	1.80	0.76	2.12
2	97.80	98.33	98.95	96.87	98.18	98.03	0.77	0.78	0.34	0.95
3	98.94	99.07	99.79	98.40	98.38	98.92	0.58	0.59	0.26	0.72
4	99.17	99.48	99.80	98.84	98.90	99.24	0.41	0.41	0.18	0.50
5	99.25	99.53	99.92	99.28	99.63	99.52	0.28	0.28	0.12	0.34
6	99.32	99.88	99.94	99.37	99.67	99.63	0.29	0.29	0.13	0.35
7	99.53	99.82	99.90	99.58	99.90	99.74	0.18	0.18	0.08	0.22
8	99.69	99.91	99.92	99.75	99.98	99.85	0.12	0.12	0.06	0.15
9	99.74	99.89	99.93	99.85	99.97	99.88	0.09	0.09	0.04	0.11

Table 9: Comparison of the oil pick-up from feathers, F (%), amongst 4 different atomised grades. The individual profiles for each grade are presented in Tables 1, 3, 5 and 7. F% is the mean for 5 replicate measurements.

	A40S-coarse atomised un-annealed grade		A100S- fine atomised un-annealed grade		ASC100.29-fine atomised annealed grade		ASC300 superfine atomised annealed	
N	F%	SE	F%	SE	F%	SE	F%	SE
1	70.97	1.58	84.72	1.78	89.07	0.45	91.37	0.87
2	83.11	1.58	92.56	1.13	93.11	1.38	94.44	0.55
3	87.91	1.58	94.87	0.52	97.45	0.43	97.23	0.35
4	91.03	1.68	96.44	0.42	98.37	0.24	98.43	0.34
5	94.08	1.27	97.23	0.34	98.60	0.18	98.82	0.23
6	95.58	0.97	97.67	0.35	98.82	0.16	99.36	0.11
7	97.00	0.37	98.12	0.31	99.08	0.03	99.48	0.08
8	97.56	0.37	98.56	0.13	99.11	0.04	99.57	0.04
9	98.11	0.28	98.76	0.08	99.09	0.03	99.59	0.04

Table 10: Comparison of the oil pick-up from feathers, F (%), amongst 4 different spongy grades. The individual profiles for each grade are presented in Tables 2, 4, 6 and 8. F% is the mean for 5 replicate measurements.

	M40-coarse spongy un-annealed grade		**C100-29-fine spongy un-annealed grade**		**NC100.24-fine spongy annealed grade**		**MH300.29-superfine spongy annealed grade**	
N	F%	SE	F%	SE	F%	SE	F%	SE
1	85.76	2.02	90.20	1.24	91.47	0.80	94.68	0.76
2	92.00	0.85	92.22	1.22	94.51	0.60	98.03	0.34
3	94.75	0.84	95.21	0.60	96.80	0.59	98.92	0.26
4	96.63	0.11	97.28	0.47	97.70	0.44	99.24	0.18
5	97.38	0.29	98.02	0.27	98.72	0.09	99.52	0.12
6	97.82	0.16	98.34	0.27	98.97	0.08	99.63	0.13
7	98.21	0.15	98.61	0.19	99.13	0.07	99.74	0.08
8	98.42	0.11	98.98	0.12	99.29	0.05	99.85	0.06
9	98.70	0.11	99.22	0.08	99.42	0.06	99.88	0.04

Table 11: Particle size of iron powder grades and their maximum contaminant removal, F_o %, from feathers

N	**Grade**	**Particle size (micron)**	**F_o(%)**	**Number of treatments**
1	A40S	274	98.11	9
2	M40S	185	98.7	9
3	A100S	80	98.76	9
4	ASC100.29	93	99.09	9
5	C100.29	89	99.22	9
6	NC100.24	100	99.42	9
7	ASC300	36	99.59	9
8	MH300.29	37	99.98	9

Table 12: Comparison of the oil pick-up from feathers, F (%), between atomised and spongy coarse un-annealed grades.

N	**A40S- atomised coarse un-annealed grade**		**M40- spongy coarse un-annealed grade**	
	F%	SE	F%	SE
1	70.97	1.58	85.76	2.02
2	83.11	1.58	92.00	0.85
3	87.91	1.58	94.75	0.84
4	91.03	1.68	96.63	0.11
5	94.08	1.27	97.38	0.29
6	95.58	0.97	97.82	0.16

7	97.00	0.37	98.21	0.15
8	97.56	0.37	98.42	0.11
9	98.11	0.28	98.70	0.11

Table 13: Comparison of the oil pick-up from feathers, F (%), between atomised and spongy fine un-annealed grades. F% is the mean for 5 replicate measurements.

N	A100S- atomised fine un-annealed grade		C100-29- spongy fine un-annealed grade	
	F%	SE	F%	SE
1	84.72	1.78	90.20	1.24
2	92.56	1.13	92.22	1.22
3	94.87	0.52	95.21	0.60
4	96.44	0.42	97.28	0.47
5	97.23	0.34	98.02	0.27
6	97.67	0.35	98.34	0.27
7	98.12	0.31	98.61	0.19
8	98.56	0.13	98.98	0.12
9	98.76	0.08	99.22	0.08

Table 14: Comparison of the oil pick-up from feathers, F (%), between atomised and spongy fine annealed grades.

N	ASC100.29- atomised fine annealed grade		NC100.24- spongy fine annealed grade	
	F%	SE	F%	SE
1	89.07	0.45	91.47	0.80
2	93.11	1.38	94.51	0.60
3	97.45	0.43	96.80	0.59
4	98.37	0.24	97.70	0.44
5	98.60	0.18	98.72	0.09
6	98.82	0.16	98.97	0.08
7	99.08	0.03	99.13	0.07
8	99.11	0.04	99.29	0.05
9	99.09	0.03	99.42	0.06

Table 15: Comparison of the oil pick-up from feathers, F (%), between atomised and spongy superfine annealed grades.

N	ASC300- atomised superfine annealed grade	MH300.29 - spongy superfine annealed grade

	F%	SE	F%	SE
1	91.37	0.87	94.68	0.76
2	94.44	0.55	98.03	0.34
3	97.23	0.35	98.92	0.26
4	98.43	0.34	99.24	0.18
5	98.82	0.23	99.52	0.12
6	99.36	0.11	99.63	0.13
7	99.48	0.08	99.74	0.08
8	99.57	0.04	99.85	0.06
9	99.59	0.04	99.88	0.04

Table 16: Comparison of the oil pick-up from feathers, F (%), between annealed and un-annealed fine spongy grades.

N	**C100-29- un-annealed fine spongy grade**		**NC100.24- annealed fine spongy grade**	
	F%	SE	F%	SE
1	90.20	1.24	91.47	0.80
2	92.22	1.22	94.51	0.60
3	95.21	0.60	96.80	0.59
4	97.28	0.47	97.70	0.44
5	98.02	0.27	98.72	0.09
6	98.34	0.27	98.97	0.08
7	98.61	0.19	99.13	0.07
8	98.98	0.12	99.29	0.05
9	99.22	0.08	99.42	0.06

Table 17: Comparison of the oil pick-up from feathers, F (%), between annealed and un-annealed atomised fine grades.

N	**A100S- un-annealed fine atomised grade**		**ASC100.29- un-annealed fine atomised grade**	
	F%	SE	F%	SE
1	84.72	1.78	89.07	0.45
2	92.56	1.13	93.11	1.38
3	94.87	0.52	97.45	0.43
4	96.44	0.42	98.37	0.24
5	97.23	0.34	98.60	0.18
6	97.67	0.35	98.82	0.16
7	98.12	0.31	99.08	0.03
8	98.56	0.13	99.11	0.04
9	98.76	0.08	99.09	0.03

Table 18: Comparison of the initial and maximum oil pick-up from a petri dish, P (%), amongst all iron powder grades.

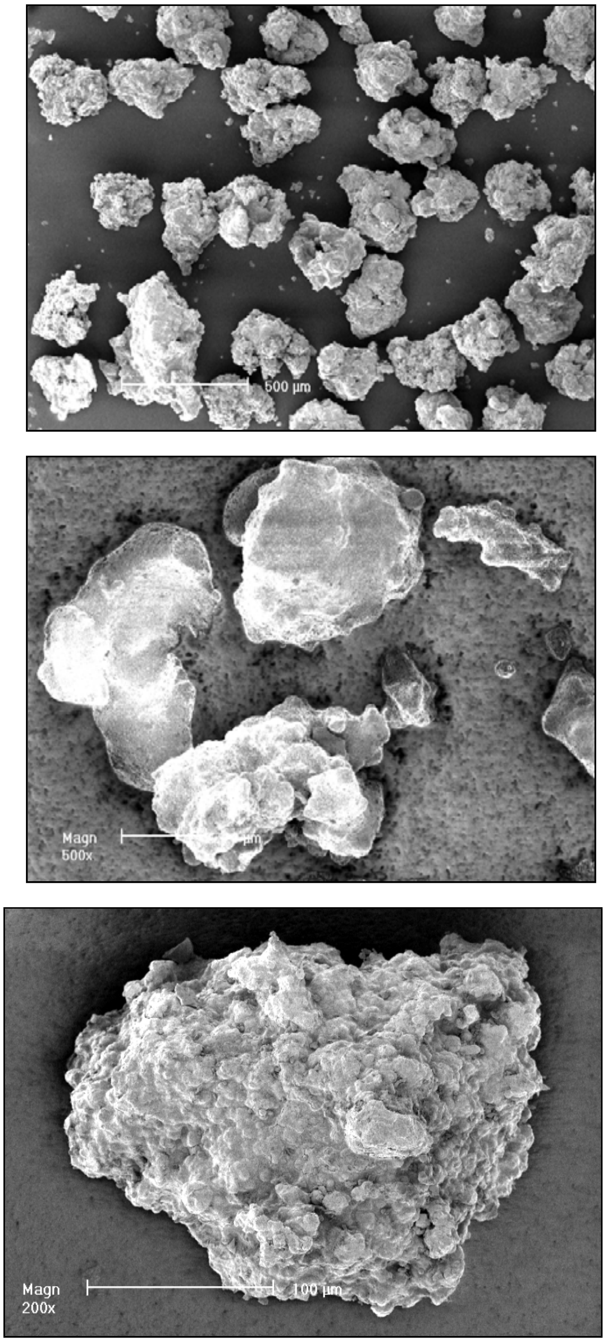
	A40S	ASC100.29	A100S	M40S	ASC300	NC100.24	C100.29	MH300.29
Initial removal (%)	28.11	31.81	36.72	36.35	39.75	39.84	40.53	40.84
SE	0.339	0.620	0.468	0.929	1.055	1.653	0.652	1.574
Maximum removal (%)	93.3	98.96	99.09	99.34	99.32	99.47	99.75	99.99
SE	0.169	0.104	0.122	0.101	0.054	0.317	0.094	0.058

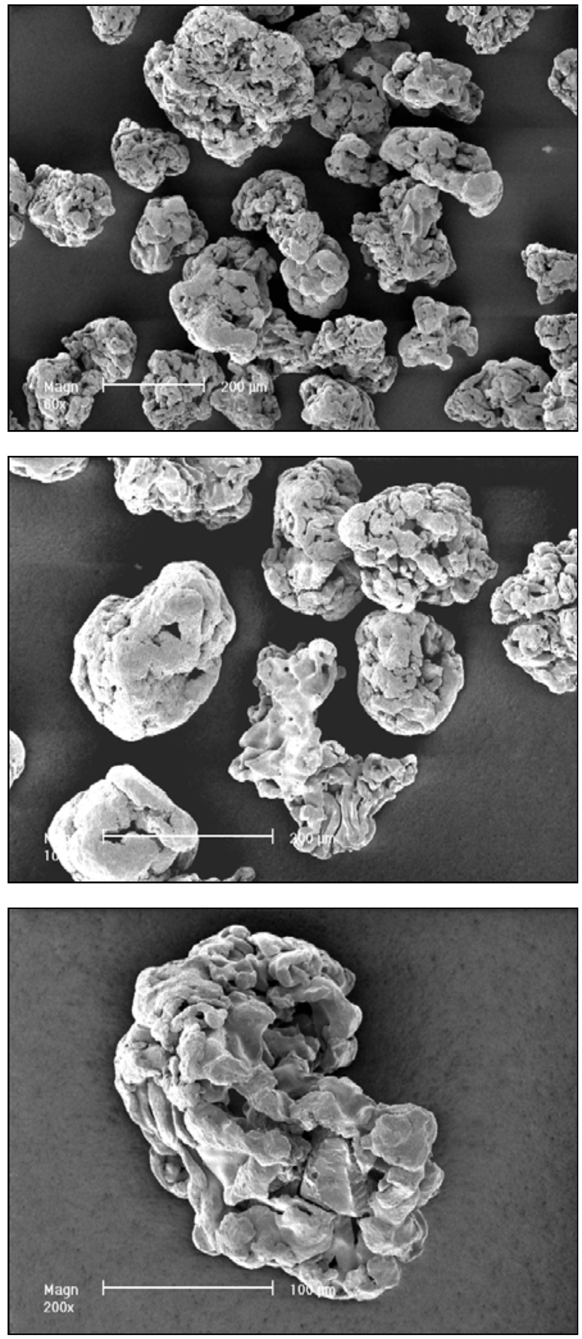
Table 19: Comparison of the oil pick-up, F (%), from feathers for all iron powder grades.

	A40S		A100S		ASC100.29		ASC300		M40		C100.29		NC100.24		MH300.29	
N	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE
1	70.97	1.58	84.72	1.78	85.76	2.02	90.20	1.24	91.47	0.80	94.68	0.76	89.07	0.45	91.37	0.87
2	83.11	1.58	92.56	1.13	92.00	0.85	92.22	1.22	94.51	0.60	98.03	0.34	93.11	1.38	94.44	0.55
3	87.91	1.58	94.87	0.52	94.75	0.84	95.21	0.60	96.80	0.59	98.92	0.26	97.45	0.43	97.23	0.35
4	91.03	1.68	96.44	0.42	96.63	0.11	97.28	0.47	97.70	0.44	99.24	0.18	98.37	0.24	98.43	0.34
5	94.08	1.27	97.23	0.34	97.38	0.29	98.02	0.27	98.72	0.09	99.52	0.12	98.60	0.18	98.82	0.23
6	95.58	0.97	97.67	0.35	97.82	0.16	98.34	0.27	98.97	0.08	99.63	0.13	98.82	0.16	99.36	0.11
7	97.00	0.37	98.12	0.31	98.21	0.15	98.61	0.19	99.13	0.07	99.74	0.08	99.08	0.03	99.48	0.08
8	97.56	0.37	98.56	0.13	98.42	0.11	98.98	0.12	99.29	0.05	99.85	0.06	99.11	0.04	99.57	0.04
9	98.11	0.28	98.76	0.08	98.70	0.11	99.22	0.08	99.42	0.06	99.88	0.04	99.09	0.03	99.59	0.04

Appendix 3.3

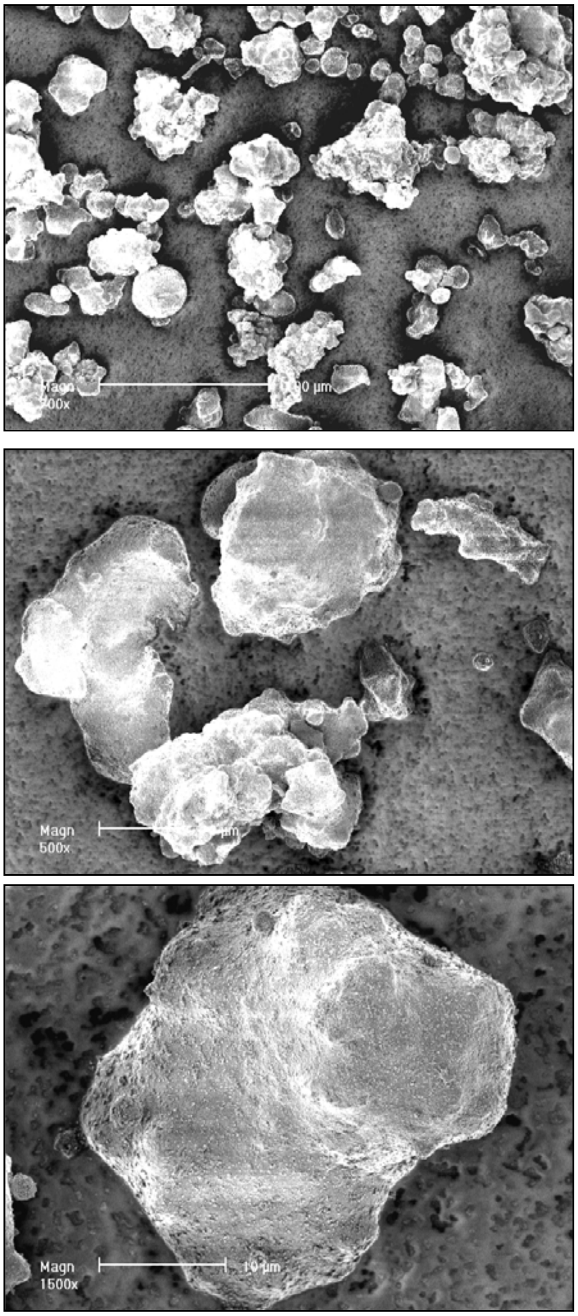
SEM of iron powder grades



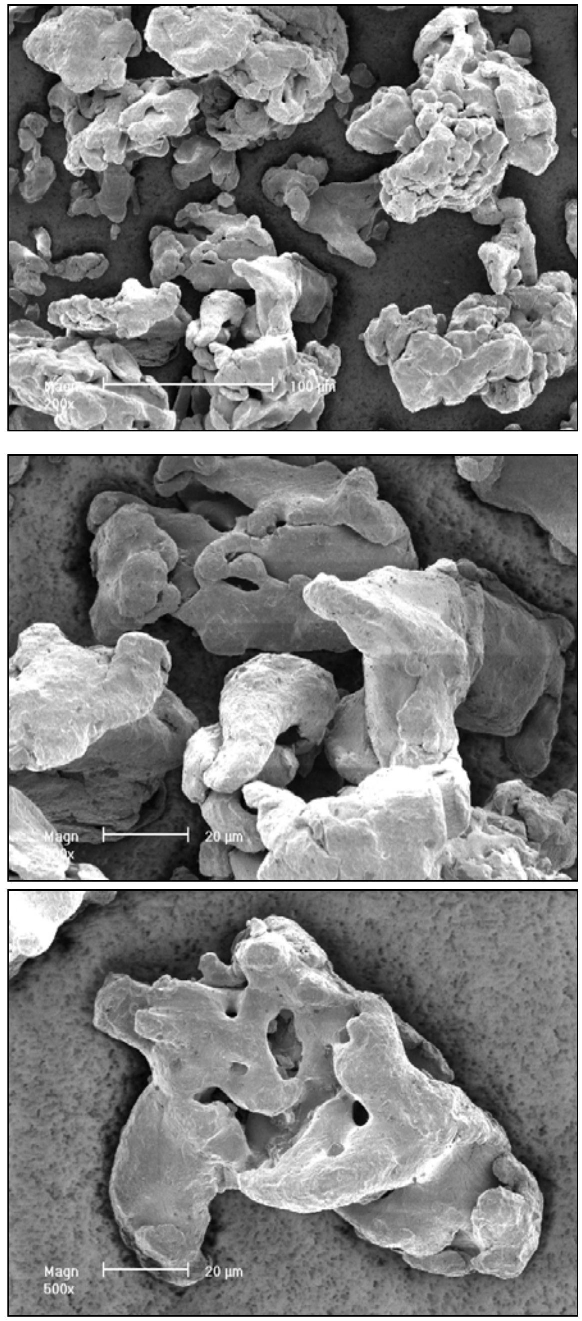


A40S-coarse atomised un-annealed grade

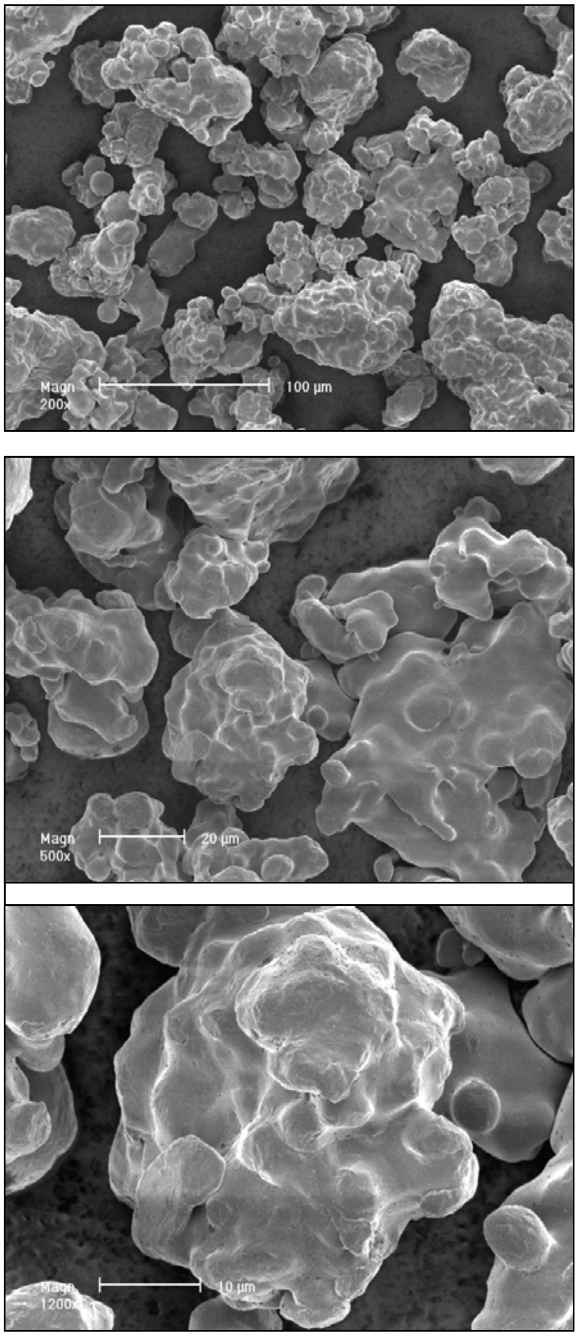
M40-coarse spongy un-annealed grade



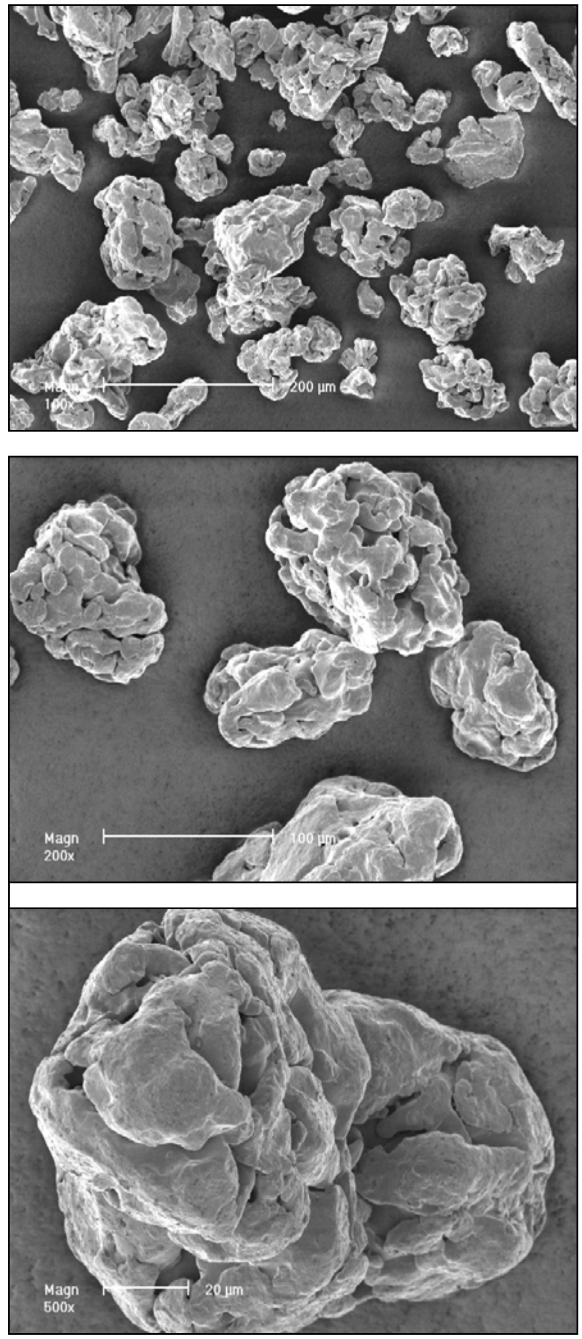
A100S-fine atomised un-annealed grade



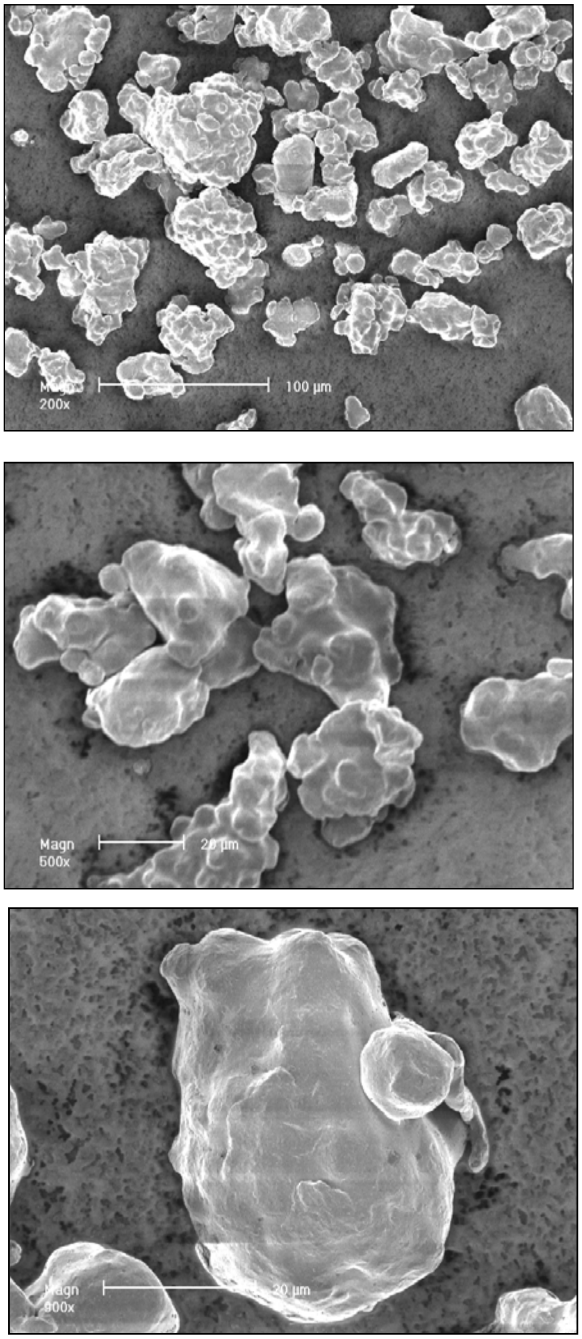
C100.29-fine spongy un-annealed grade

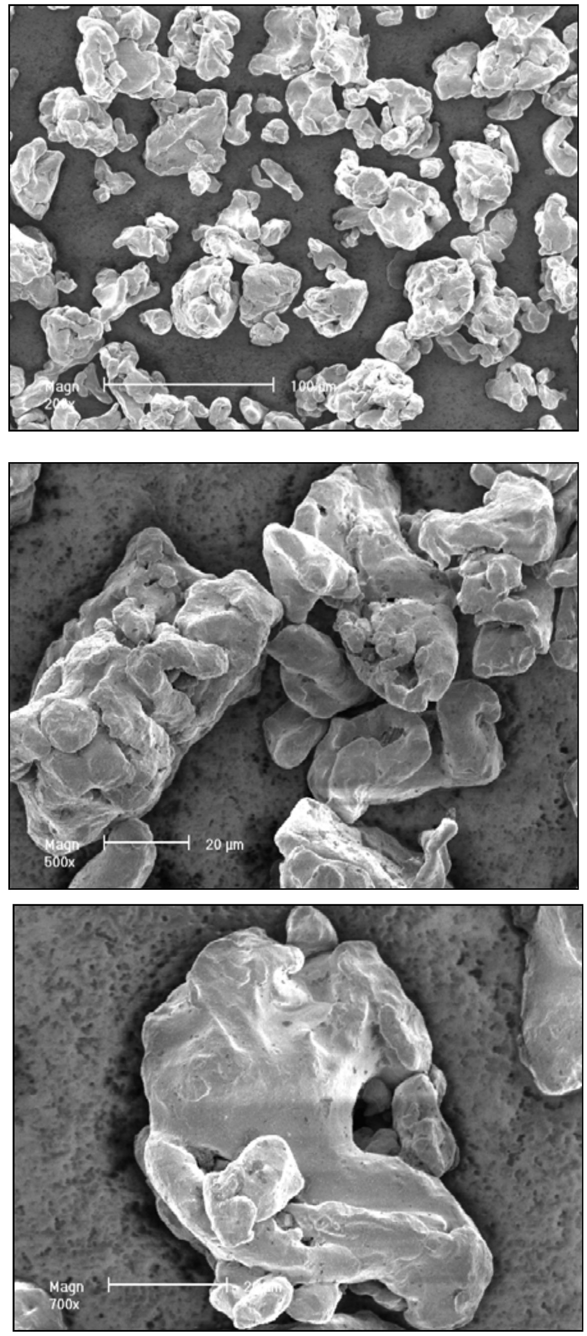


ASC100.29-fine atomised annealed grade

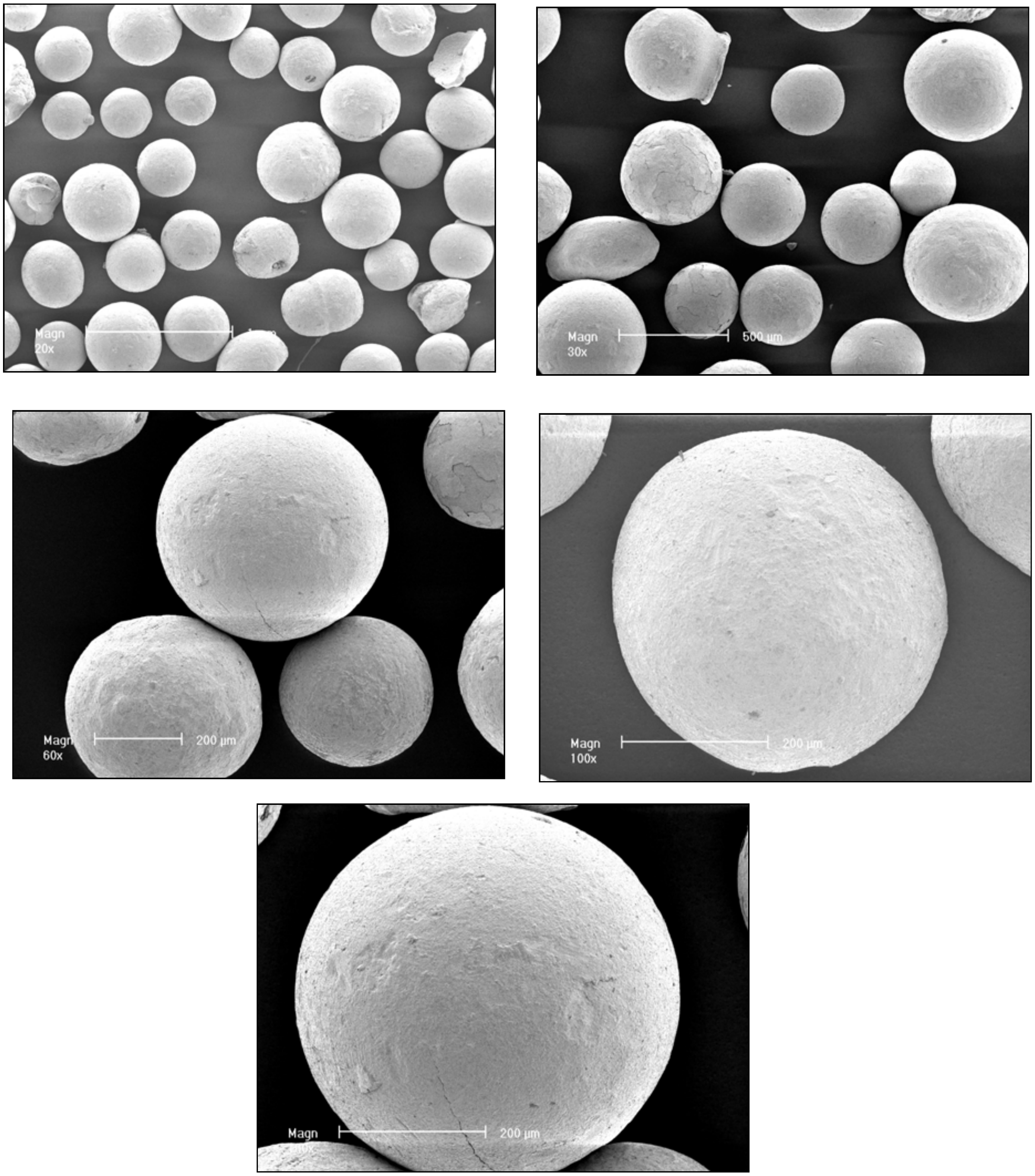


NC100.24-fine spongy annealed grade





ASC300-superfine atomised annealed grade **MH300.29-superfine spongy annealed grade**



Original grade

Appendix 4.1

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Table 1: Comparison of the pick-up, P (%), from a petri dish amongst light, medium and heavy oils, using the optimal grade - MH300.29. Experiments were conducted in five replicates.

GO			MO			AO			EO			BO1		
R	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**
1	46.19	2.00	1	45.18	2.77	1	40.84	4.37	1	59.18	4.47	1	81.83	3.53
2	64.78	2.53	2	63.00	1.55	2	60.90	4.04	2	85.33	2.39	2	89.59	2.63
3	80.70	1.67	3	77.50	2.75	3	83.40	4.09	3	92.75	1.80	3	93.79	1.22
4	86.60	2.19	4	86.20	3.06	4	93.00	2.21	4	96.32	0.58	4	96.88	0.75
6	92.00	2.45	6	94.00	1.49	6	98.00	1.23	6	97.86	0.88	6	98.32	0.74
8	94.00	1.26	8	96.00	1.47	8	98.77	0.51	8	98.78	0.22	8	99.31	0.47
10	95.40	1.34	10	97.50	2.28	10	99.30	0.17	10	99.45	0.39	10	99.70	0.15
12	96.60	2.23	12	97.86	0.78	12	99.85	0.34	12	99.68	0.21	12	99.82	0.12
14	97.50	0.75	14	98.75	0.31	14	100.00	0.16						
16	98.19	0.72	16	99.25	0.49									
18	98.33	0.36	18	99.60	0.25									

Table 2: Comparison of the pick-up, P (%), from a petri dish between oils and their respective emulsions using the optimal grade - MH300.29. Experiments were conducted in five replicates

GO			EO			ES1			ES2		
R	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**
1	46.19	2.00	1	59.18	4.47	1	45.84	3.67	1	71.60	6.07
2	64.78	2.53	2	85.33	2.39	2	63.60	2.59	2	83.30	3.04
3	80.70	1.67	3	92.75	1.80	3	81.64	1.67	3	91.00	1.53
4	86.60	2.19	4	96.32	0.58	4	90.90	2.03	4	96.83	0.44
6	92.00	2.45	6	97.86	0.88	6	96.61	0.96	6	99.53	0.10
8	94.00	1.26	8	98.78	0.22	8	98.35	0.55	8	99.69	0.14
10	95.40	1.34	10	99.45	0.39	10	99.18	0.23	10	99.60	0.35
12	96.60	2.23	12	99.68	0.21	12	99.74	0.21	12	99.70	0.16
14	97.50	0.75									
16	98.19	0.72									
18	98.33	0.36									

Table 3: Comparison of the pick-up, P (%), from a petri dish amongst all the fresh oils and emulsions, using the optimal grade - MH300.29. Experiments were conducted in five replicates.

GO			MO			AO			EO			BO1			ES1			ES2		
R	**P(%)**	**SE**	**R**	**P(%)**	**SE**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**	**R**	**P(%)**	**95%**
1	46.19	0.72	1	45.18	1.00	1	40.84	1.57	1	59.18	1.61	1	81.83	1.27	1	45.84	1.32	1	71.60	2.19
2	64.78	0.91	2	63.00	0.56	2	60.90	1.46	2	85.33	0.86	2	**89.59**	**0.95**	2	63.60	0.93	2	83.30	1.10
3	80.70	0.60	3	77.50	0.99	3	83.40	1.47	3	92.75	0.65	3	93.79	0.44	3	81.64	0.60	3	91.00	0.55
4	86.60	0.79	4	86.20	1.10	4	93.00	0.80	4	96.32	0.21	4	96.88	0.27	4	90.90	0.73	4	96.83	0.16
6	92.00	0.88	6	94.00	0.54	6	98.00	0.44	6	97.86	0.32	6	98.32	0.27	6	96.61	0.35	6	99.53	0.04
8	94.00	0.45	8	96.00	0.53	8	98.77	0.18	8	98.78	0.08	8	99.31	0.17	8	98.35	0.20	8	99.69	0.05
10	95.40	0.48	10	97.50	0.82	10	99.30	0.06	10	99.45	0.14	10	99.70	0.05	10	99.18	0.08	10	99.60	0.13
12	96.60	0.80	12	97.26	0.28	12	99.85	0.12	12	99.68	0.08	12	99.82	0.04	12	99.74	0.08	12	99.70	0.06
14	97.50	0.27	14	98.05	0.11	14	100.00	0.06												
16	98.19	0.26	16	99.25	0.18															
18	98.33	0.13	18	99.60	0.09															

Table 4: Blank tests on duck cluster feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (B%)					B%(mean)	S	%CV	SE	95%
1	99.206	99.248	99.378	101.195	99.129	99.631	0.879	0.882	0.393	1.091
2	99.364	99.062	99.844	101.357	98.842	99.694	1.003	1.006	0.448	1.245
3	100.644	100.380	100.000	100.954	100.294	100.454	0.362	0.360	0.162	0.449
4	99.840	99.248	99.688	100.714	99.708	99.840	0.537	0.538	0.240	0.667
5	100.321	99.811	99.533	101.034	99.854	100.111	0.589	0.588	0.263	0.731

Table 5: The removal of AO, F (%), from duck breast feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	94.26	95.57	96.36	91.94	95.27	94.68	1.71	1.80	0.76	2.12
2	97.80	98.33	98.95	96.87	98.18	98.03	0.77	0.78	0.34	0.95
3	98.94	99.07	99.79	98.40	98.38	98.92	0.58	0.59	0.26	0.72
4	99.17	99.48	99.80	98.84	98.90	99.24	0.41	0.41	0.18	0.50
5	99.25	99.53	99.92	99.28	99.63	99.52	0.28	0.28	0.12	0.34
6	99.32	99.88	99.94	99.37	99.67	99.63	0.29	0.29	0.13	0.35
7	99.53	99.82	99.90	99.58	99.90	99.74	0.18	0.18	0.08	0.22
8	99.69	99.91	99.92	99.75	99.98	99.85	0.12	0.12	0.06	0.15
9	99.74	99.89	99.93	99.85	99.97	99.88	0.09	0.09	0.04	0.11

Table 6: The removal of GO, F (%), from duck breast feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	96.99	98.69	99.21	99.44	99.58	98.78	1.06	1.07	0.47	1.31
2	99.29	100.00	100.03	99.86	100.08	99.85	0.32	0.32	0.14	0.40
3	100.35	99.96	99.95	99.96	100.16	100.08	0.18	0.18	0.08	0.22
4	100.50	100.16	100.29	99.95	100.14	100.21	0.21	0.21	0.09	0.26
5	100.41	100.28	100.21	99.95	100.09	100.19	0.18	0.18	0.08	0.22
6	100.45	100.12	100.13	100.00	100.05	100.15	0.18	0.17	0.08	0.22
7	100.37	100.20	100.24	100.07	100.10	100.20	0.12	0.12	0.05	0.15

Table 7: The removal of ES1, F (%), from duck feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	96.50	98.37	97.73	95.51	94.20	96.46	1.68	1.74	0.75	2.08
2	98.04	99.56	98.69	99.28	96.51	98.42	1.21	1.23	0.54	1.51
3	98.77	99.78	99.71	99.52	98.09	99.17	0.73	0.73	0.33	0.90
4	99.42	99.90	99.86	99.62	98.55	99.47	0.55	0.55	0.25	0.68
5	99.54	100.00	99.95	99.86	99.69	99.81	0.19	0.19	0.08	0.24
6	99.93	100.01	100.04	100.07	99.97	100.00	0.05	0.05	0.02	0.07
7	99.97	100.01	100.03	100.03	100.25	100.06	0.11	0.11	0.05	0.13

Table 8: The removal of MO, F (%), from duck breast feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	96.91	96.97	98.36	96.91	97.37	97.30	0.62	0.64	0.28	0.77
2	99.42	98.97	99.33	99.29	99.00	99.20	0.20	0.21	0.09	0.25
3	99.57	99.77	99.79	99.81	99.82	99.75	0.11	0.11	0.05	0.13
4	99.69	99.93	99.94	100.15	100.01	99.94	0.17	0.17	0.07	0.21
5	99.74	100.03	99.95	100.23	100.06	100.00	0.18	0.18	0.08	0.22
6	99.86	100.02	99.98	100.19	100.06	100.02	0.12	0.12	0.05	0.15
7	99.92	100.00	99.99	100.20	100.14	100.05	0.11	0.11	0.05	0.14
8	99.95	100.01	99.97	100.21	100.12	100.05	0.11	0.11	0.05	0.14

Table 9: The removal of ES2, F (%), from duck breast feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	65.43	74.78	51.79	64.05	77.27	66.66	10.10	15.15	4.52	12.54
2	90.60	91.01	82.44	81.02	93.04	87.62	5.48	6.25	2.45	6.80
3	97.23	96.57	91.97	92.39	97.34	95.10	2.69	2.82	1.20	3.33
4	98.39	96.90	98.71	98.96	99.06	98.41	0.88	0.89	0.39	1.09
5	99.16	98.67	99.41	99.16	99.73	99.23	0.39	0.39	0.17	0.48
6	99.30	99.34	99.80	99.55	99.85	99.57	0.25	0.25	0.11	0.31

7	99.67	99.77	99.87	99.73	99.91	99.79	0.10	0.10	0.04	0.12
8	99.93	99.97	99.89	99.86	99.93	99.92	0.04	0.04	0.02	0.05
9	100.02	100.00	99.91	99.84	99.88	99.93	0.08	0.08	0.04	0.10

Table 10: The removal of EO, F (%), from duck feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	76.70	69.55	74.26	73.28	73.77	73.51	2.57	3.50	1.15	3.20
2	92.86	91.15	88.69	91.56	88.85	90.62	1.81	1.99	0.81	2.24
3	98.04	96.40	97.49	98.11	99.02	97.81	0.96	0.98	0.43	1.20
4	99.37	99.14	99.50	99.70	99.68	99.48	0.23	0.23	0.10	0.29
5	99.89	99.46	99.83	99.87	100.08	99.82	0.23	0.23	0.10	0.28
6	99.93	100.10	99.88	99.99	100.15	100.01	0.11	0.11	0.05	0.14
7	99.99	100.17	99.88	100.08	100.19	100.06	0.13	0.13	0.06	0.16
8	100.01	100.19	99.89	100.10	100.20	100.08	0.13	0.13	0.06	0.16
9	100.05	100.19	99.88	100.11	100.19	100.08	0.13	0.13	0.06	0.16

Table 11: The removal of BO1, F (%), from duck breast feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	65.58	58.24	59.78	65.78	55.30	60.94	4.62	7.58	2.07	5.74
2	81.95	84.93	83.78	85.98	77.78	82.88	3.22	3.88	1.44	4.00
3	94.71	93.75	92.24	92.99	89.82	92.70	1.85	2.00	0.83	2.30
4	99.11	97.92	96.51	97.00	94.81	97.07	1.60	1.65	0.72	1.99
5	99.46	99.50	99.38	99.34	97.89	99.12	0.69	0.69	0.31	0.85
6	99.57	99.62	99.70	99.52	99.24	99.53	0.18	0.18	0.08	0.22
7	99.76	99.77	99.85	99.60	99.34	99.66	0.20	0.21	0.09	0.25
8	99.82	99.83	99.87	99.61	99.41	99.71	0.19	0.19	0.09	0.24
9	99.82	99.84	99.87	99.61	99.45	99.72	0.18	0.18	0.08	0.23

Table 12: Comparison of pick-up, F (%), from duck feathers amongst light, medium and heavy oils, using the optimal grade - MH300.29.

N	GO		MO		AO		EO		BO1	
	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE
1	98.78	0.47	97.30	0.28	94.68	0.76	73.51	1.15	60.90	2.05
2	99.85	0.14	99.20	0.09	98.03	0.34	90.62	0.81	82.88	1.44

3	100.08	0.08	99.75	0.05	98.92	0.26	97.81	0.43	92.70	0.83
4	100.21	0.09	99.94	0.08	99.24	0.18	99.48	0.10	97.07	0.72
5	100.19	0.08	100.00	0.08	99.52	0.12	99.82	0.10	99.12	0.31
6	100.15	0.08	100.02	0.05	99.63	0.13	100.01	0.05	99.53	0.08
7	100.20	0.05	100.05	0.05	99.74	0.08	100.06	0.06	99.66	0.09
8			100.05	0.05	99.85	0.05	100.08	0.06	99.71	0.09
9					99.88	0.04	100.08	0.06	99.72	0.08

Table 13: Comparison of pick-up, F (%), from duck feathers between oils and their respective emulsions, using the optimal grade - MH300.29.

N	GO		EO		ES1		ES2	
	F%	SE	F%	SE	F%	SE	F%	SE
1	98.78	0.47	73.51	1.15	96.46	0.75	66.66	4.52
2	99.85	0.14	90.62	0.81	98.42	0.54	87.62	2.45
3	100.08	0.08	97.81	0.43	99.17	0.32	95.10	1.20
4	100.21	0.09	99.48	0.10	99.47	0.24	98.41	0.39
5	100.19	0.08	99.82	0.10	99.81	0.09	99.23	0.17
6	100.15	0.08	100.01	0.05	100.00	0.03	99.57	0.11
7	100.20	0.05	100.06	0.06	100.06	0.05	99.79	0.04
8			100.08	0.06		0.00	99.92	0.02
9			100.08	0.06			99.93	0.04

Table 14: Comparison of pick-up, F (%), from duck feathers amongst all oils and emulsions, using the optimal grade - MH300.29.

N	GO		MO		AO		EO		BO1		ES1		ES2	
	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE
1	98.78	0.47	97.30	0.28	94.68	0.76	73.51	1.15	60.90	2.05	96.46	0.75	66.66	4.52
2	99.85	0.14	99.20	0.09	98.03	0.34	90.62	0.81	82.88	1.44	98.42	0.54	87.62	2.45
3	100.08	0.08	99.75	0.05	98.92	0.26	97.81	0.43	92.70	0.83	99.17	0.32	95.10	1.20
4	100.21	0.09	99.94	0.08	99.24	0.18	99.48	0.10	97.07	0.72	99.47	0.24	98.41	0.39
5	100.19	0.08	100.00	0.08	99.52	0.12	99.82	0.10	99.12	0.31	99.81	0.09	99.23	0.17
6	100.15	0.08	100.02	0.05	99.63	0.13	100.01	0.05	99.53	0.08	100.00	0.03	99.57	0.11
7	100.20	0.05	100.05	0.05	99.74	0.08	100.06	0.06	99.66	0.09	100.06	0.05	99.79	0.04
8			100.05	0.05	99.85	0.05	100.08	0.06	99.71	0.09		0.00	99.92	0.02
9					99.88	0.04	100.08	0.06	99.72	0.08			99.93	0.04

Table 15: The removal of AO, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	96.59	97.46	97.55	97.76	96.67	97.20	0.54	0.55	0.24	0.67
2	97.21	98.21	98.16	98.21	97.60	97.88	0.45	0.46	0.20	0.56
3	98.19	98.68	98.88	98.66	98.37	98.56	0.27	0.28	0.12	0.34
4	98.68	98.68	99.39	98.88	99.07	98.94	0.30	0.30	0.13	0.37
5	99.23	99.25	99.28	99.22	99.38	99.27	0.07	0.07	0.03	0.08
6	99.65	99.44	99.49	99.55	99.54	99.53	0.08	0.08	0.04	0.10
7	99.72	99.62	99.59	99.55	99.61	99.62	0.06	0.06	0.03	0.08

Table 16: The removal of GO, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	98.13	98.27	98.15	98.15	97.91	98.12	0.13	0.13	0.06	0.16
2	98.57	98.61	98.44	98.46	98.60	98.54	0.08	0.08	0.04	0.10
3	98.90	99.08	98.72	98.77	98.74	98.84	0.15	0.15	0.07	0.18
4	99.01	99.19	99.00	98.92	99.02	99.03	0.10	0.10	0.04	0.12
5	99.12	99.31	98.86	99.08	99.16	99.11	0.16	0.16	0.07	0.20
6	99.01	99.19	99.15	99.23	99.02	99.12	0.10	0.10	0.04	0.12
7	99.12	99.31	99.15	99.08	99.16	99.16	0.09	0.09	0.04	0.11

Table 17: The removal of ES1, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	94.29	91.71	97.38	95.58	95.35	94.86	2.08	2.20	0.93	2.59
2	96.38	96.83	98.17	97.70	96.12	97.04	0.87	0.90	0.39	1.08
3	97.14	97.80	98.43	98.23	97.67	97.86	0.50	0.51	0.23	0.62
4	97.90	98.29	98.69	98.76	98.45	98.42	0.34	0.35	0.15	0.43

5	98.48	98.78	98.95	98.94	99.03	98.84	0.22	0.22	0.10	0.27
6	98.86	99.02	98.95	99.12	99.22	99.03	0.14	0.14	0.06	0.18
7	99.05	99.02	99.21	99.12	99.03	99.09	0.08	0.08	0.04	0.10

Table 18: The removal of MO, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	98.77	97.85	98.50	98.94	99.15	98.64	0.50	0.51	0.22	0.62
2	99.22	98.85	99.10	99.27	99.39	99.17	0.20	0.21	0.09	0.25
3	99.44	98.71	99.40	99.35	99.64	99.31	0.35	0.35	0.16	0.44
4	99.55	99.14	99.25	99.59	99.52	99.41	0.20	0.20	0.09	0.25
5	99.55	99.71	99.55	99.59	99.76	99.63	0.10	0.10	0.04	0.12
6	99.67	99.57	99.40	99.51	99.64	99.56	0.11	0.11	0.05	0.13
7	99.55	99.71	99.70	99.67	99.76	99.68	0.08	0.08	0.03	0.10

Table 19: The removal of ES2, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	89.90	90.76	88.41	88.30	87.52	88.98	1.32	1.48	0.59	1.64
2	95.91	95.18	93.54	93.77	94.14	94.51	1.00	1.06	0.45	1.25
3	97.24	97.46	95.36	96.23	96.15	96.49	0.86	0.89	0.38	1.07
4	98.32	98.26	96.85	96.98	97.84	97.65	0.70	0.71	0.31	0.86
5	99.04	98.53	97.19	97.92	98.15	98.17	0.69	0.70	0.31	0.86
6	99.16	98.93	97.85	98.49	98.31	98.55	0.52	0.53	0.23	0.64
7	99.28	99.06	98.18	98.68	98.46	98.73	0.44	0.45	0.20	0.55
8	99.64	99.06	98.51	98.87	98.61	98.94	0.45	0.45	0.20	0.56
9	99.52	99.20	98.68	99.06	98.77	99.04	0.34	0.34	0.15	0.42

Table 20: The removal of EO, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	96.36	96.69	95.14	95.54	99.52	96.65	1.72	1.78	0.77	2.14
2	98.52	99.01	98.97	99.46	99.95	99.18	0.54	0.55	0.24	0.67
3	99.09	99.23	99.28	99.59	99.95	99.43	0.35	0.35	0.16	0.43
4	99.32	99.34	99.38	99.66	99.96	99.53	0.28	0.28	0.12	0.35
5	99.54	99.45	99.48	99.73	99.97	99.63	0.22	0.22	0.10	0.27
6	99.66	99.56	99.59	99.80	99.96	99.71	0.17	0.17	0.07	0.21
7	99.77	99.56	99.59	99.80	99.97	99.74	0.17	0.17	0.08	0.21

Table 21: The removal of BO1, F (%), from penguin feathers using the optimal grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	83.82	87.03	84.04	75.62	80.66	82.23	4.33	5.27	1.94	5.38
2	93.67	94.83	96.53	93.05	93.26	94.27	1.44	1.53	0.64	1.79
3	94.72	98.63	98.12	96.65	96.94	97.01	1.52	1.56	0.68	1.88
4	96.60	99.68	98.69	98.33	97.99	98.26	1.12	1.14	0.50	1.39
5	98.48	99.79	98.78	98.86	98.69	98.92	0.51	0.51	0.23	0.63
6	98.71	99.47	99.06	99.03	98.78	99.01	0.30	0.30	0.13	0.37
7	98.94	99.68	99.25	99.47	98.95	99.26	0.32	0.33	0.14	0.40
8	99.06	99.58	99.44	99.47	99.13	99.33	0.23	0.23	0.10	0.28
9	99.18	99.68	99.44	99.56	99.21	99.41	0.22	0.22	0.10	0.27

Table 22: Comparison of the pick-up, F (%), from penguin feathers amongst light, medium and heavy oils, using the optimal grade - MH300.29.

	GO		MO		AO		EO		BO1	
N	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE
1	98.12	0.06	98.64	0.22	97.20	0.24	96.65	0.77	82.23	1.94
2	98.54	0.04	99.17	0.09	97.88	0.20	99.18	0.24	94.27	0.64
3	98.84	0.06	99.31	0.16	98.56	0.12	99.43	0.15	97.01	0.68
4	99.03	0.04	99.41	0.09	98.94	0.13	99.53	0.13	98.26	0.50
5	99.11	0.07	99.63	0.04	99.27	0.03	99.63	0.10	98.92	0.23

6	99.12	0.04	99.56	0.05	99.53	0.04	99.71	0.08	99.01	0.13
7	99.16	0.04	99.68	0.04	99.62	0.03	99.74	0.08	99.26	0.14
									99.33	0.10
									99.41	0.10

Table 23: Comparison of the pick-up, F (%), from penguin feathers between oils and their respective emulsions, using the optimal grade - MH300.29.

	GO		**EO**		**ES1**		**ES2**	
N	F%	SE	F%	SE	F%	SE	F%	SE
1	98.12	0.06	96.65	0.77	94.86	0.93	88.98	0.59
2	98.54	0.04	99.18	0.24	97.04	0.39	94.51	0.45
3	98.84	0.06	99.43	0.15	97.86	0.22	96.49	0.39
4	99.03	0.04	99.53	0.13	98.42	0.15	97.65	0.31
5	99.11	0.07	99.63	0.10	98.84	0.10	98.17	0.31
6	99.12	0.04	99.71	0.08	99.03	0.06	98.55	0.23
7	99.16	0.04	99.74	0.08	99.09	0.04	98.73	0.20
							98.94	0.20
							99.04	0.15

Table 24: Comparison of the pick-up, F (%), from penguin feathers amongst all oils and emulsions, using the optimal grade - MH300.29.

	GO		**MO**		**AO**		**EO**		**BO1**		**ES1**		**ES2**	
N	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE	F%	SE
1	98.12	0.06	98.64	0.22	97.20	0.24	96.65	0.77	82.23	1.94	94.86	0.93	88.98	0.59
2	98.54	0.04	99.17	0.09	97.88	0.20	99.18	0.24	94.27	0.64	97.04	0.39	94.51	0.45
3	98.84	0.06	99.31	0.16	98.56	0.12	99.43	0.15	97.01	0.68	97.86	0.22	96.49	0.39
4	99.03	0.04	99.41	0.09	98.94	0.13	99.53	0.13	98.26	0.50	98.42	0.15	97.65	0.31
5	99.11	0.07	99.63	0.04	99.27	0.03	99.63	0.10	98.92	0.23	98.84	0.10	98.17	0.31
6	99.12	0.04	99.56	0.05	99.53	0.04	99.71	0.08	99.01	0.13	99.03	0.06	98.55	0.23
7	99.16	0.04	99.68	0.04	99.62	0.03	99.74	0.08	99.26	0.14	99.09	0.04	98.73	0.20
									99.33	0.10			98.94	0.20
									99.41	0.10			99.04	0.15

Table 25: Comparison of the pick-up, F (%), of EO between duck and penguin feathers, using the optimal grade - MH300.29.

	Duck		**Penguin**	
N	F%	SE	F%	SE
1	73.51	1.15	96.65	0.77
2	90.62	0.81	99.18	0.24
3	97.81	0.43	99.43	0.15
4	99.48	0.10	99.53	0.13
5	99.82	0.10	99.63	0.10
6	100.01	0.05	99.71	0.08
7	100.06	0.06	99.74	0.08
8	100.08	0.06		
9	100.08	0.06		

Table 26: Comparison of the pick-up, F (%), ES2 between duck and penguin feathers, using the optimal grade - MH300.29.

	Duck		Penguin	
N	F%	SE	F%	SE
1	66.66	4.52	88.98	0.59
2	87.62	2.45	94.51	0.45
3	95.10	1.20	96.49	0.39
4	98.41	0.39	97.65	0.31
5	99.23	0.17	98.17	0.31
6	99.57	0.11	98.55	0.23
7	99.79	0.04	98.73	0.20
8	99.92	0.02	98.94	0.20
9	99.93	0.04	99.04	0.15

Table 27: Comparison of the pick-up, F (%), of GO between duck and penguin feathers, using the optimal grade - MH300.29.

	Duck		Penguin	
N	F%	SE	F%	SE
1	98.78	0.47	98.12	0.06
2	99.85	0.14	98.54	0.04
3	100.08	0.08	98.84	0.06
4	100.21	0.09	99.03	0.04
5	100.19	0.08	99.11	0.07
6	100.15	0.08	99.12	0.04
7	100.20	0.05	99.16	0.04

Table 28: Comparison of the pick-up, F (%), of ES1 between duck and penguin feathers, using the optimal grade - MH300.29.

N	Duck		Penguin	
	F%	SE	F%	SE
1	96.46	0.75	94.86	0.93
2	98.42	0.54	97.04	0.39
3	99.17	0.32	97.86	0.22
4	99.47	0.24	98.42	0.15
5	99.81	0.09	98.84	0.10
6	100.00	0.03	99.03	0.06
7	100.06	0.05	99.09	0.04

Appendix 4.2

Abbreviation

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Table 1: The removal of BO1, C (%), from plumage, using the optimal iron powder grade. MH300.29. Experiments were conducted in five-patch replicate.

N	Five replicates (%)					C%(mean)	S	%CV	SE	95%
1	34.40	35.93	27.92	39.22	37.89	35.07	4.402	12.551	1.969	5.465
2	50.57	55.44	41.79	53.51	57.69	51.80	6.175	11.921	2.762	7.666
3	64.34	68.92	63.77	68.23	69.70	66.99	2.740	4.090	1.225	3.401
4	72.85	76.44	72.50	75.64	77.73	75.03	2.282	3.041	1.020	2.833
5	81.90	83.70	80.19	84.31	86.40	84.30	2.370	2.811	1.060	2.942
6	87.48	87.25	84.18	89.08	90.33	88.66	2.316	2.613	1.036	2.876
7	88.92	90.32	89.72	93.89	92.93	91.16	2.144	2.352	0.959	2.662
8	92.35	93.62	91.32	94.95	95.79	93.61	1.830	1.955	0.818	2.272
9	94.40	94.61	93.21	96.45	96.31	95.00	1.372	1.445	0.614	1.704
10	95.02	96.02	94.11	97.51	97.23	95.98	1.440	1.500	0.644	1.788

Table 2: The removal of AO, C (%), from plumage, using the optimal iron powder grade, MH300.29. Experiments were conducted in five-patch replicate.

N	**Five replicates (%)**					**C%(mean)**	**S**	**%CV**	**SE**	**95%**
1	36.16	42.22	46.28	35.41	42.32	40.48	4.59	11.35	2.05	5.70
2	51.05	57.28	62.10	56.94	58.55	57.18	3.99	6.98	1.78	4.95
3	66.32	67.90	66.67	73.65	69.28	68.76	2.97	4.32	1.33	3.69
4	75.00	76.05	73.66	80.45	77.10	76.45	2.57	3.37	1.15	3.20
5	83.68	81.98	80.65	84.14	83.19	82.73	1.42	1.71	0.63	1.76
6	89.47	85.93	84.68	90.08	87.25	87.48	2.30	2.62	1.03	2.85
7	92.63	90.37	88.98	93.77	90.14	91.18	1.96	2.15	0.88	2.43
8	95.00	92.84	92.74	96.32	93.33	94.05	1.56	1.66	0.70	1.94
9	96.32	95.06	95.16	97.45	95.94	95.99	0.97	1.01	0.44	1.21
10	97.11	96.05	97.04	98.30	96.81	97.06	0.81	0.83	0.36	1.01

Table 3: The removal of GO, C (%), from plumage, using the optimal iron powder grade, MH300.29. Experiments were conducted in five-patch replicate.

N	**Five replicates (%)**					**C%(mean)**	**S**	**%CV**	**SE**	**95%**
1	42.07	40.87	36.49	41.13	46.30	41.37	3.50	8.45	1.56	4.34
2	62.79	52.74	64.39	62.88	67.02	61.96	5.43	8.77	2.43	6.74
3	75.90	66.89	74.39	69.50	78.01	72.94	4.61	6.32	2.06	5.72
4	81.82	75.80	80.70	79.20	84.99	80.50	3.38	4.20	1.51	4.20
5	85.84	84.47	85.79	85.34	88.58	86.01	1.54	1.79	0.69	1.91
6	89.01	88.81	89.82	89.36	92.18	89.84	1.36	1.52	0.61	1.69
7	92.18	92.69	92.28	92.43	95.98	93.11	1.62	1.74	0.72	2.01
8	95.56	94.98	94.21	94.33	96.83	95.18	1.07	1.12	0.48	1.33
9	96.62	97.03	95.79	96.45	97.89	96.76	0.77	0.80	0.35	0.96
10	97.25	97.95	96.67	97.40	98.73	97.60	0.78	0.80	0.35	0.97

Table 4: The removal of EO, C (%), from plumage, using the optimal iron powder grade, MH300.29. Experiments were conducted in five-patch replicate.

N	Five replicates (%)					C%(mean)	S	%CV	SE	95%
1	42.34	41.40	33.56	34.96	38.90	38.23	3.870	10.122	1.731	4.804
2	61.49	60.25	40.21	48.18	59.73	53.97	9.382	17.383	4.196	11.647
3	71.07	73.04	56.46	63.89	66.70	66.23	6.536	9.869	2.923	8.115
4	74.33	82.67	71.58	72.11	75.44	75.23	4.451	5.917	1.991	5.526
5	76.25	86.38	78.52	83.56	82.52	81.44	4.050	4.973	1.811	5.028
6	82.18	90.51	82.89	90.32	86.99	86.58	3.955	4.568	1.769	4.910
7	89.66	91.88	86.79	94.80	91.26	90.88	2.947	3.243	1.318	3.659
8	92.53	95.74	91.44	95.73	93.24	93.74	1.933	2.062	0.864	2.400
9	95.02	97.39	94.87	96.46	95.73	95.89	1.048	1.093	0.469	1.302
10	96.74	98.62	95.34	97.09	97.09	96.98	1.169	1.205	0.523	1.451

Table 5: Comparison of removal from plumage, C (%), using the optimal iron powder grade, MH300.29, amongst all contaminants.

	EO		**AO**		**GO**		**BO1**	
N	**C (%)**	**SE**	**C (%)**	**SE**	**C (%)**	**SE**	**C (%)**	**SE**
1	38.231	1.73	40.478	2.05	41.373	1.56	**35.07**	1.97
2	53.972	4.20	57.185	1.78	61.964	2.43	51.80	2.76
3	66.234	2.92	68.763	1.33	72.939	2.06	66.99	1.22
4	75.226	1.99	76.452	1.15	80.501	1.51	75.03	1.02
5	81.444	1.81	82.726	0.63	86.005	0.69	84.30	1.06
6	86.580	1.77	87.482	1.03	89.837	0.61	88.66	1.04
7	90.877	1.32	91.179	0.88	93.114	0.72	91.16	0.96
8	93.736	0.86	94.046	0.70	95.181	0.48	93.61	0.82
9	95.894	0.47	95.986	0.44	96.756	0.35	95.00	0.61
10	96.977	0.52	97.062	0.36	97.599	0.35	95.98	0.64

Table 6: Comparison of the removal of GO between clusters and plumage, using the optimal iron powder grade, MH300.29.

N	Plumage		Feather cluster	
	C%	**95%**	**C%**	**95%**
1	41.37	4.34	98.12	0.16
2	61.96	6.74	98.54	0.10
3	72.94	5.72	98.84	0.18
4	80.50	4.20	99.03	0.12
5	86.01	1.91	99.11	0.20
6	89.84	1.69	99.12	0.12
7	93.11	2.01	99.16	0.11
8	95.18	1.33		
9	96.76	0.96		
10	97.60	0.97		

Table 7: Comparison of the removal of AO between feather clusters and plumage, using the optimal iron powder grade, MH300.29.

N	Plumage		Feather cluster	
	C%	**95%**	**C%**	**95%**
1	40.48	5.70	97.20	0.67
2	57.18	4.95	97.88	0.56
3	68.76	3.69	98.56	0.34
4	76.45	3.20	98.94	0.37
5	82.73	1.76	99.27	0.08
6	87.48	2.85	99.53	0.10
7	91.18	2.43	99.62	0.08
8	94.05	1.94		
9	95.99	1.21		
10	97.06	1.01		

Table 8: Comparison of the removal of EO between feather clusters and plumage, using the optimal iron powder grade, MH300.29.

N	Plumage		Feather cluster	
	C%	**95%**	**C%**	**95%**
1	38.23	4.80	96.65	2.14
2	53.97	11.65	99.18	0.67
3	66.23	8.11	99.43	0.43
4	75.23	5.53	99.53	0.35
5	81.44	5.03	99.63	0.27
6	86.58	4.91	99.71	0.21
7	90.88	3.66	99.74	0.21
8	93.74	2.40		

9	95.89	1.30		
10	96.98	1.45		

Table 9: Comparison of the removal of BO1 between feather clusters and plumage, using the optimal iron powder grade, MH300.29.

N	**Plumage**		**Feather cluster**	
	C%	**95%**	**C%**	**95%**
1	35.07	5.46	82.233	5.375
2	51.80	7.67	94.267	1.786
3	66.99	3.40	97.014	1.884
4	75.03	2.83	98.257	1.394
5	84.30	2.94	98.918	0.630
6	88.66	2.88	99.010	0.373
7	91.16	2.66	99.260	0.402
8	93.61	2.27		
9	95.00	1.70		
10	95.98	1.79		

Table 10: Comparison of the maximum oil removals amongst a petri dish, duck and penguin feathers for all contaminants using the optimal iron powder grade, MH300.29.

Contaminants	Petri dish		Duck feathers		Penguin feathers	
	F%	95%	F%	95%	F%	95%
GO	98.33	0.36	100.20	0.15	99.16	0.11
MO	99.60	0.25	100.05	0.14	99.68	0.10
AO	100	0.16	99.88	0.11	99.62	0.08
EO	99.68	0.21	100.08	0.16	99.74	0.21
BO1	99.82	0.12	99.72	0.23	99.41	0.27
ES1	99.74	0.21	100.06	0.13	99.09	0.10
ES2	99.70	0.16	99.93	0.10	99.04	0.42

Figure 1: The preparation of carcasses before experiments.

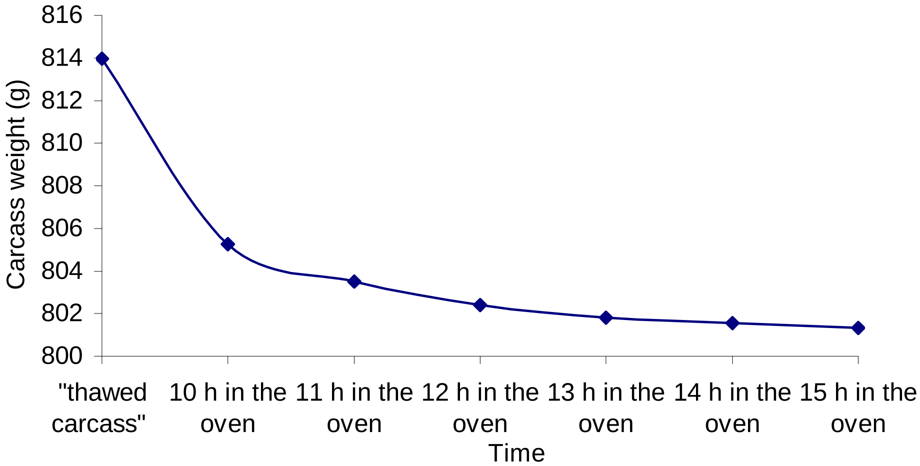


Figure 2: The changing of the weight of a carcass, from the time it was taken out of a cold room until it was ready for experiments.

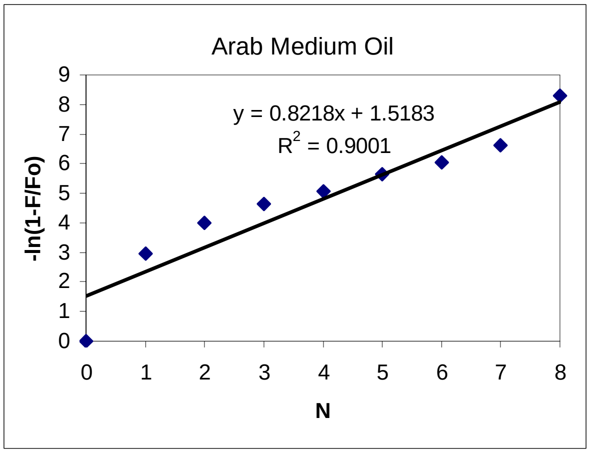


Figure 3: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of AO from duck feathers, using the optimal iron powder grade, MH300.29.

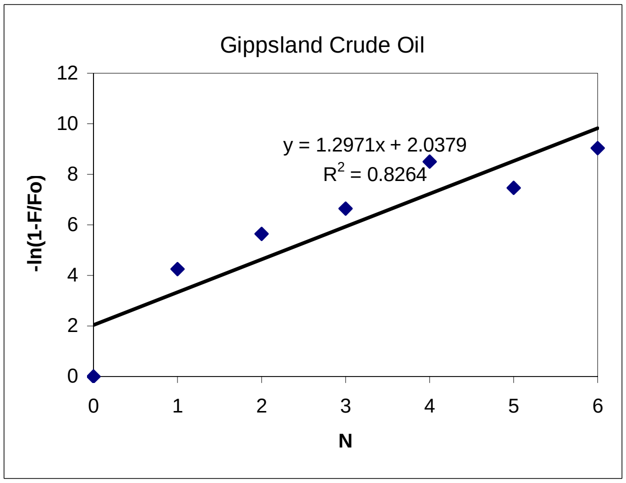


Figure 4: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of GO from duck feathers, using the optimal iron powder grade, MH300.29.

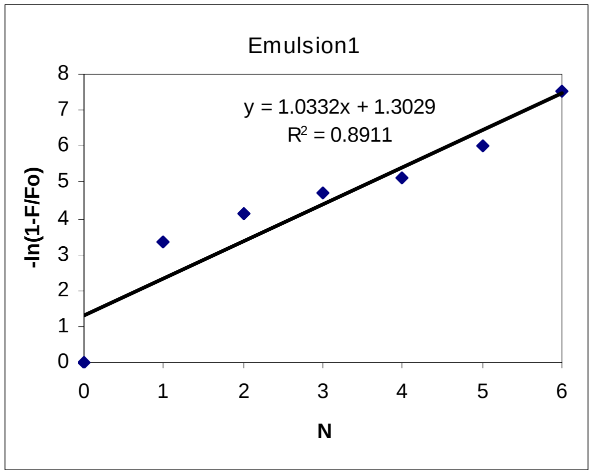


Figure 5: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of ES1 from duck feathers, using the optimal iron powder grade, MH300.29.

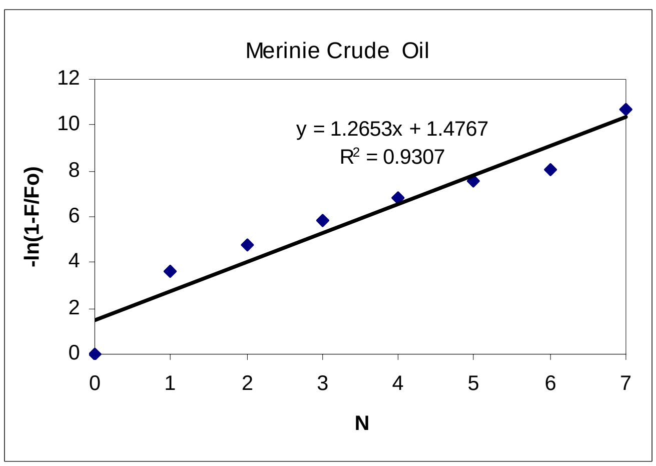


Figure 6: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of MO from duck feathers, using the optimal iron powder grade, MH300.29.

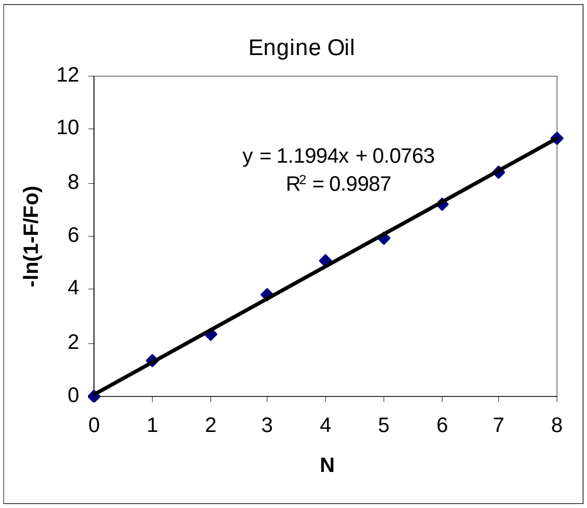


Figure 7: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of EO from duck feathers, using the optimal iron powder grade, MH300.29.

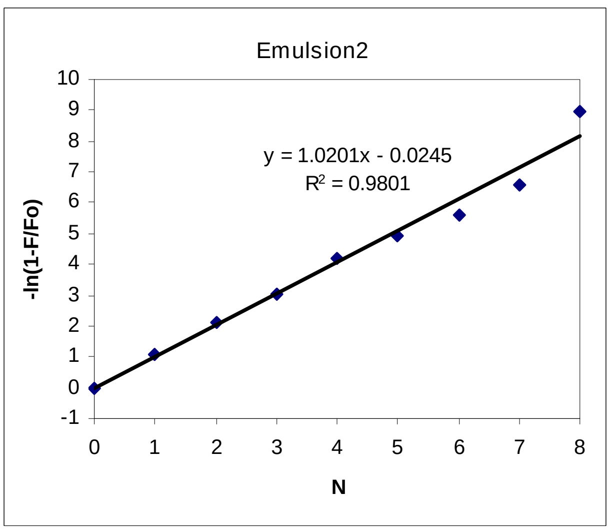


Figure 8: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of ES2 from duck feathers, using the optimal iron powder grade, MH300.29.

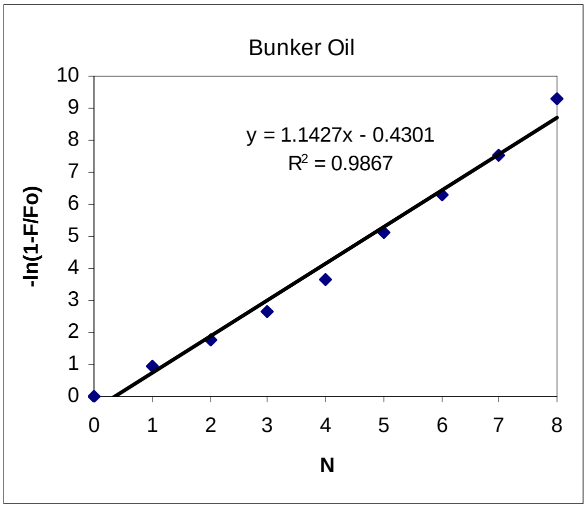


Figure 9: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of BO1 from duck feathers, using the optimal iron powder grade, MH300.29.

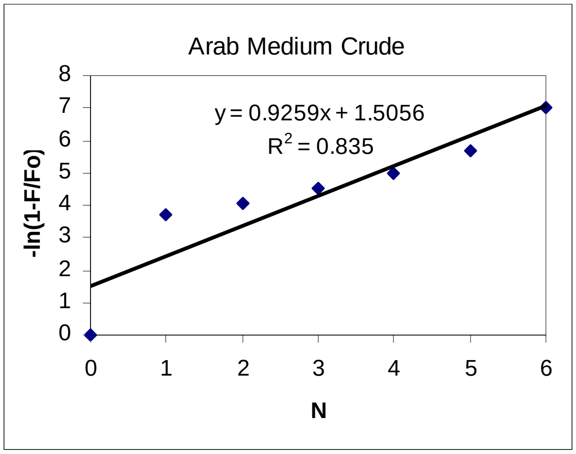


Figure 10: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of AO from penguin feathers, using the optimal iron powder grade, MH300.29.

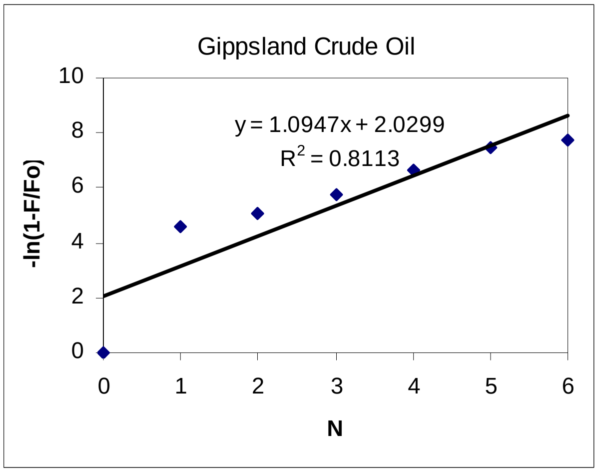


Figure 11 Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of GO from penguin feathers, using the optimal iron powder grade, MH300.29.

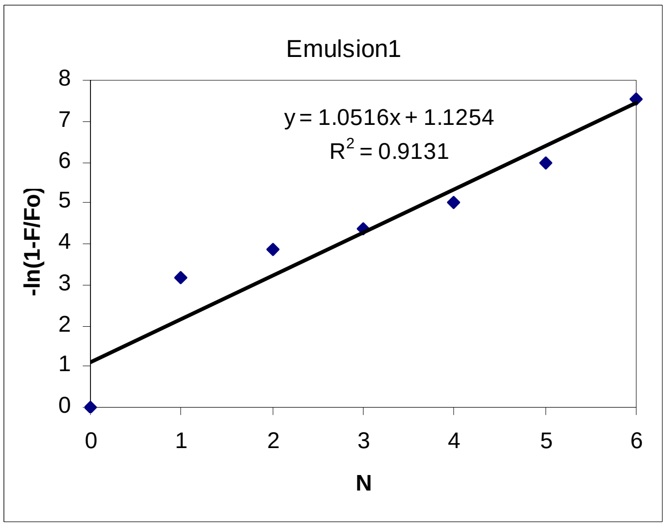


Figure 12: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of ES1 from penguin feathers, using the optimal iron powder grade, MH300.29.

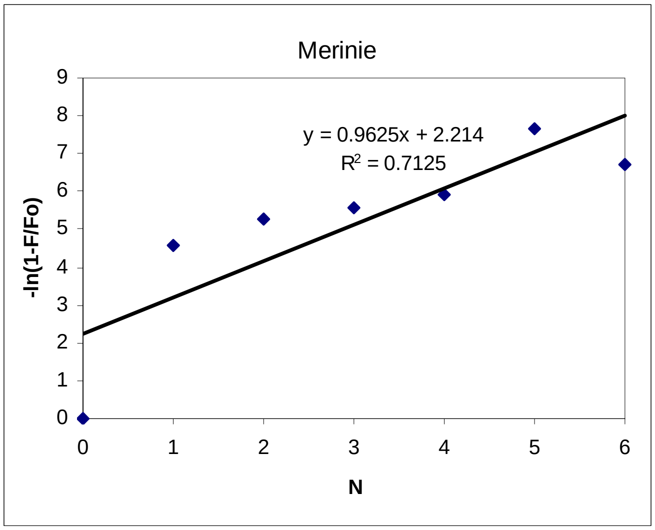


Figure 13: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of MO from penguin feathers, using the optimal iron powder grade, MH300.29.

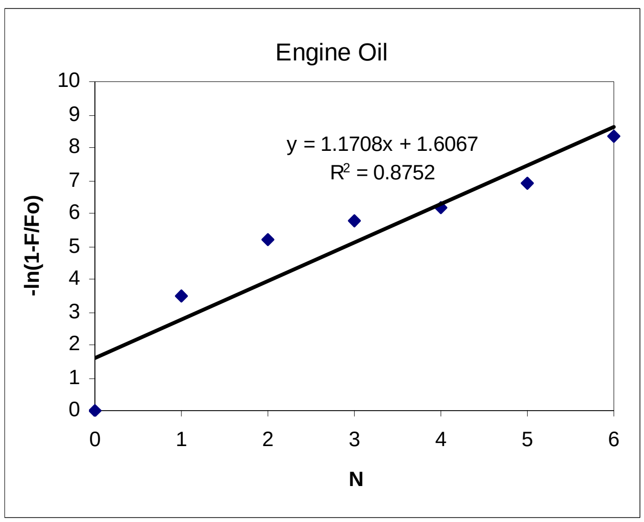


Figure 14: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of EO from penguin feathers, using the optimal iron powder grade, MH300.29.

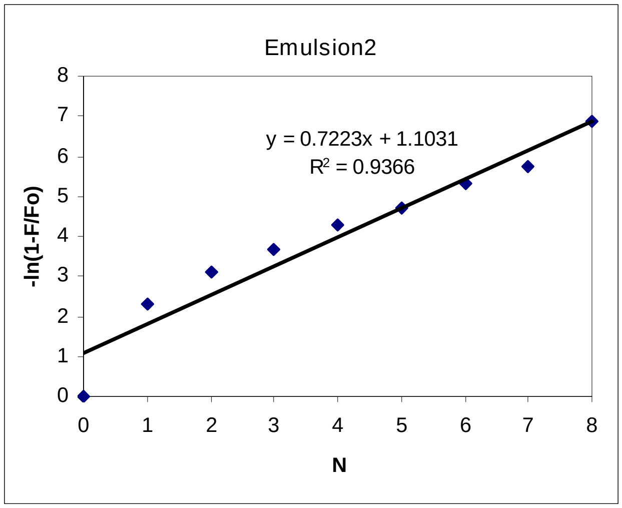


Figure 15: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of ES2 from penguin feathers, using the optimal iron powder grade, MH300.29.

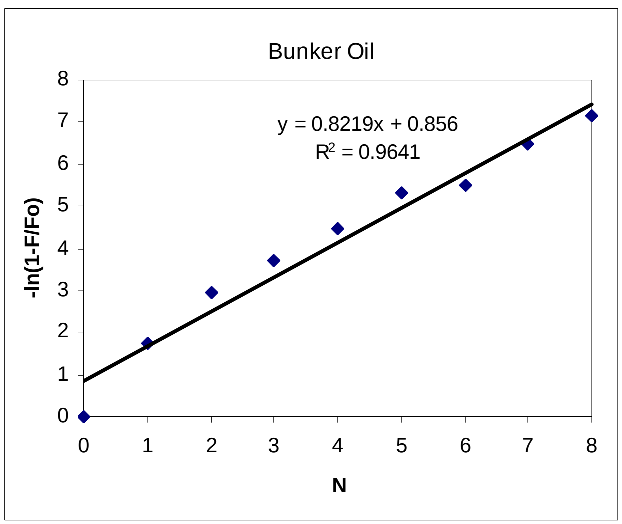


Figure 16: Plot of -ln (1-F/F_o) versus the number of treatments, N, for the removal efficiency of BO1 from penguin feathers, using the optimal iron powder grade, MH300.29.

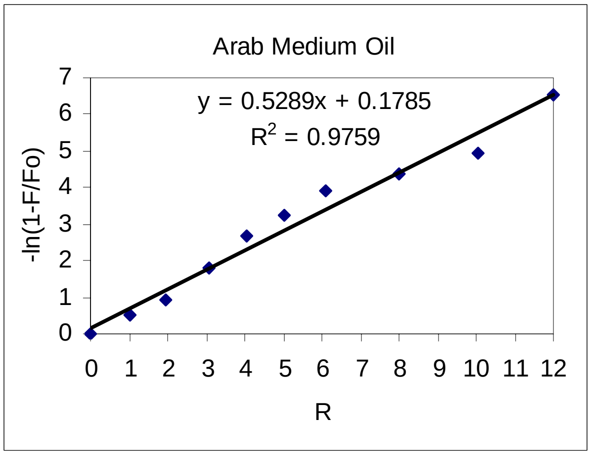


Figure 17: Plot of -ln (1-F/F_o) the particle-to-contaminant ratio, R, for the removal efficiency of AO from a petri dish, using the optimal iron powder grade, MH300.29.

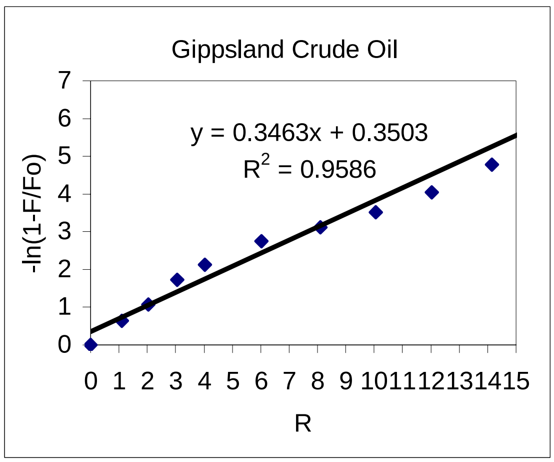


Figure 18: Plot of -ln (1-F/F_o) versus the particle-to-contaminant ratio, R, for the removal efficiency of GO from a petri dish, using the optimal iron powder grade, MH300.29.

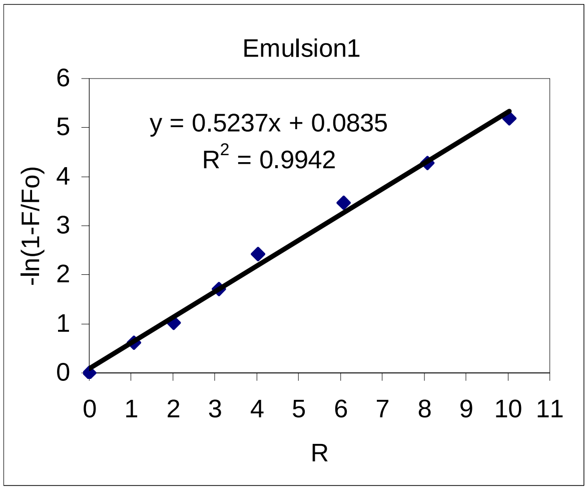


Figure 19: Plot of -ln (1-F/F_o) versus the particle-to-contaminant ratio, R, for the removal efficiency of ES1 from a petri dish, using the optimal iron powder grade, MH300.29.

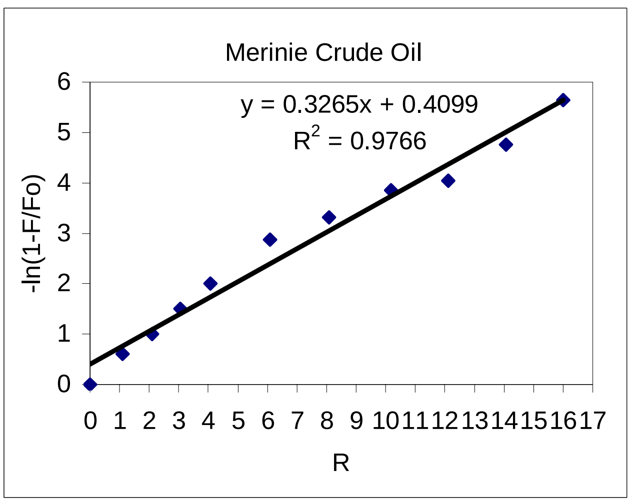


Figure 20: Plot of -ln (1-F/F_o) versus the particle-to-contaminant ratio, R, for the removal efficiency of MO from a petri dish, using the optimal iron powder grade, MH300.29.

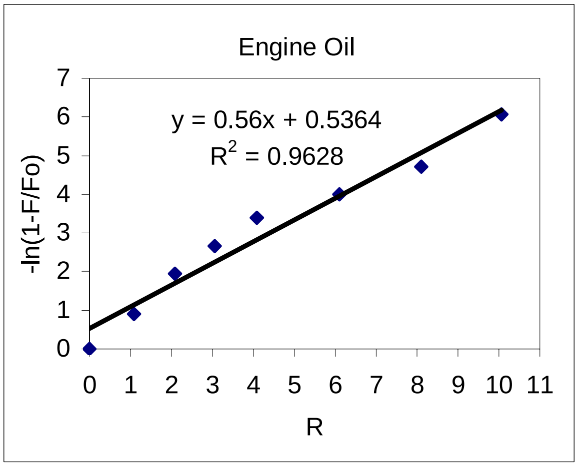


Figure 21: Plot of -ln $(1-F/F_o)$ versus the particle-to-contaminant ratio, R, for the removal efficiency of EO from a petri dish, using the optimal iron powder grade, MH300.29.

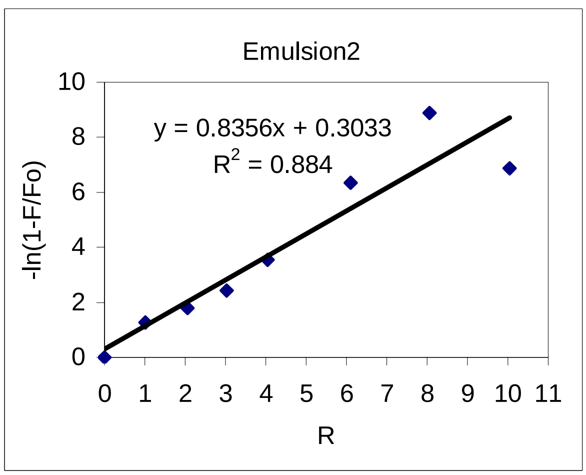


Figure 22: Plot of -ln $(1-F/F_o)$ versus the particle-to-contaminant ratio, R, for the removal efficiency of ES2 from a petri dish, using the optimal iron powder grade, MH300.29.

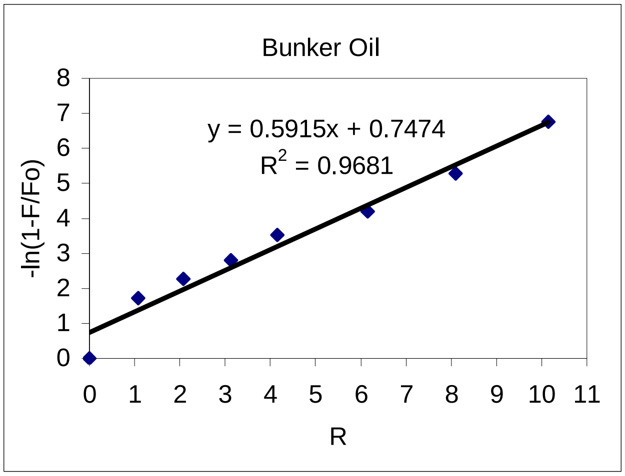


Figure 23: Plot of -ln (1-F/F_o) versus the particle-to-contaminant ratio, R, for the removal efficiency of BO1 from a petri dish, using the optimal iron powder grade, MH300.29.

Appendix 5.1

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Table 1: Readings of the temperatures of the experiments on duck feather clusters

T1 (°C)	T2 (°C)	T3 (°C)	T(mean) (°C)	S	%CV	SE	95%
10.9	11.1	11.0	11.0	0.1	0.9	0.1	0.2
12.1	12.3	12.2	12.2	0.1	0.8	0.1	0.2
13.5	14.0	14.4	14.0	0.5	3.2	0.3	1.1
15.1	15.5	15.8	15.5	0.4	2.3	0.2	0.9
17.0	17.3	17.7	17.3	0.4	2.0	0.2	0.9
20.1	20.2	20.4	20.2	0.2	0.8	0.1	0.4
22.3	22.4	22.4	22.4	0.1	0.3	0.0	0.1
25.0	25.5	26.0	25.5	0.5	2.0	0.3	1.2
27.3	27.4	27.9	27.5	0.3	1.2	0.2	0.8

Table 2: The removal of tarry Shell crude oil (SO) from duck feather clusters, using the optimal iron powder grade - MH300.29, for all treatments is represented as a function of nine different ambient temperatures from 11°C to 27.5°C. Experiments were conducted in five replicates at different ambient temperatures for all treatments.

Ambient temperature		1 treatment		2 treatments		3 treatments		4 treatments		5 treatments	
T mean (°C)	S	F%	95%	F%	95%	F%	95%	F%	95%	F%	95%
11.0	0.1	0	0	0	0	0	0	0	0	0	0
12.2	0.1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14.0	0.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15.5	0.4	22.412	4.300	35.953	7.940	50.527	8.490	63.997	10.008	75.963	4.753
17.3	0.4	26.471	2.938	50.931	7.936	68.900	10.976	84.175	8.262	92.741	6.819
20.2	0.2	59.119	10.362	79.779	15.177	91.174	11.916	96.772	4.259	98.727	1.326
22.4	0.1	66.103	12.362	83.433	6.137	92.662	7.408	96.834	3.116	98.432	0.953
25.5	0.5	67.851	9.779	88.107	9.972	94.408	7.800	97.550	3.124	98.764	0.993
27.5	0.3	68.884	7.964	88.484	10.453	95.556	7.095	97.433	4.307	98.476	2.131

Table 2 (cont.): The removal of tarry Shell crude contaminant (SO) from duck feather clusters, using the optimal iron powder grade MH300.29, for all treatments is represented as a function of nine different ambient temperatures from 11^{o}C to 27.5^{o}C. Experiments were conducted in five replicates at different temperatures for all treatments.

	6 treatments		**7 treatments**		**8 treatments**		**9 treatments**		**10 treatments**	
T mean (^{o}C)	**F%**	**95%**	**F%**	**95%**	**F%**	**95%**	**F%**	**95%**	**F%**	**95%**
11.0	0	0	0	0	0	0	0	0	0	0
12.2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15.5	85.204	8.259	91.772	4.892	95.729	1.373	97.104	0.849	97.948	0.312
17.3	95.361	5.139	97.111	2.588	98.184	1.118	98.573	0.869	98.835	0.720
20.2	99.282	0.620	99.493	0.419	99.561	0.377	99.638	0.296	99.651	0.274
22.4	99.036	0.536	99.243	0.463	99.304	0.417	99.389	0.346	99.431	0.325
25.5	99.057	0.618	99.213	0.553	99.330	0.468	99.463	0.342	99.531	0.299
27.5	99.096	0.928	99.330	0.556	99.450	0.371	99.509	0.319	99.547	0.262

Table 3: The removal, F (%), of tarry Shell crude contaminant (SO) from duck feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 15.5^{o}C.

N	**Five replicates (F%)**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	22.406	27.677	17.947	21.904	22.124	22.412	3.464	15.456	1.549	4.300
2	35.998	39.034	24.927	39.078	40.726	35.953	6.396	17.789	2.860	7.940
3	45.319	52.824	42.613	51.849	60.030	50.527	6.839	13.535	3.058	8.490
4	53.483	64.035	59.104	69.757	73.605	63.997	8.062	12.597	3.605	10.008
5	72.204	73.302	74.146	79.771	80.392	75.963	3.828	5.040	1.712	4.753
6	78.083	80.519	82.949	92.687	91.782	85.204	6.652	7.807	2.975	8.259
7	87.342	88.940	90.843	95.725	96.012	91.772	3.941	4.294	1.762	4.892
8	94.105	96.077	95.216	96.255	96.991	95.729	1.106	1.155	0.495	1.373
9	95.939	97.076	97.393	97.662	97.450	97.104	0.684	0.705	0.306	0.849
10	97.561	98.087	98.233	97.954	97.902	97.948	0.251	0.257	0.112	0.312

Table 4: The removal, F (%) of tarry Shell crude contaminant (SO) from duck feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 17.3^{o}C.

N	**Five replicates (F%)**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	24.920	29.680	24.380	25.070	28.303	26.471	2.366	8.939	1.058	2.938

2	47.023	56.449	44.252	47.976	58.955	50.931	6.392	12.551	2.859	7.936
3	71.625	81.855	61.898	59.526	69.596	68.900	8.841	12.831	3.954	10.976
4	84.289	93.332	82.035	74.984	86.236	84.175	6.655	7.906	2.976	8.262
5	95.400	97.683	93.704	83.380	93.539	92.741	5.493	5.923	2.457	6.819
6	97.790	97.956	97.363	88.159	95.539	95.361	4.139	4.341	1.851	5.139
7	98.407	98.501	97.901	93.488	97.258	97.111	2.085	2.147	0.932	2.588
8	98.716	98.705	98.677	96.620	98.202	98.184	0.901	0.917	0.403	1.118
9	98.835	98.910	99.015	97.330	98.775	98.573	0.700	0.710	0.313	0.869
10	99.004	99.075	99.188	97.804	99.101	98.835	0.580	0.587	0.259	0.720

Table 5: The removal, F (%), of tarry Shell crude contaminant (SO) from duck feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 20.2^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	49.298	66.903	67.490	59.921	51.983	59.119	8.347	14.119	3.733	10.362
2	66.522	87.123	91.452	87.273	66.522	79.779	12.225	15.324	5.467	15.177
3	80.740	96.191	99.069	99.130	80.740	91.174	9.598	10.528	4.293	11.916
4	93.036	98.662	99.483	99.643	93.036	96.772	3.431	3.545	1.534	4.259
5	97.586	99.101	99.643	99.717	97.586	98.727	1.068	1.082	0.478	1.326
6	98.778	99.306	99.733	99.816	98.778	99.282	0.499	0.503	0.223	0.620
7	99.188	99.387	99.824	99.879	99.188	99.493	0.338	0.339	0.151	0.419
8	99.298	99.433	99.852	99.921	99.298	99.561	0.304	0.305	0.136	0.377
9	99.466	99.464	99.865	99.932	99.466	99.638	0.238	0.239	0.107	0.296
10	99.488	99.505	99.856	99.927	99.481	99.651	0.221	0.222	0.099	0.274

Table 6: The removal, F (%), of tarry Shell crude contaminant, using the optimal iron powder grade - MH300.29, from duck feather clusters. Experiments were conducted in five replicates at 22.4^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	54.969	68.961	72.463	77.601	56.520	66.103	9.958	15.064	4.453	12.362
2	76.180	88.351	85.519	86.435	80.680	83.433	4.943	5.924	2.211	6.137
3	85.163	97.534	97.319	96.046	87.248	92.662	5.967	6.440	2.669	7.408
4	93.229	98.422	99.248	98.007	95.262	96.834	2.510	2.592	1.122	3.116
5	97.547	98.799	99.382	98.686	97.745	98.432	0.768	0.780	0.343	0.953
6	98.387	99.143	99.590	99.087	98.974	99.036	0.432	0.436	0.193	0.536
7	98.744	99.331	99.782	99.198	99.159	99.243	0.373	0.376	0.167	0.463
8	98.812	99.352	99.758	99.314	99.284	99.304	0.336	0.338	0.150	0.417
9	99.034	99.384	99.817	99.359	99.351	99.389	0.279	0.281	0.125	0.346
10	99.092	99.436	99.827	99.411	99.387	99.431	0.262	0.263	0.117	0.325

Table 7: The removal, F (%), of tarry Shell crude contaminant from duck feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 25.5°C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	74.625	66.494	76.683	63.959	57.493	67.851	7.877	11.609	3.523	9.779
2	93.923	90.366	95.761	84.537	75.949	88.107	8.032	9.117	3.592	9.972
3	98.089	97.503	97.745	95.373	83.330	94.408	6.283	6.655	2.810	7.800
4	99.242	99.294	98.259	97.751	93.204	97.550	2.517	2.580	1.126	3.124
5	99.424	99.470	98.987	98.368	97.574	98.764	0.799	0.809	0.358	0.993
6	99.515	99.571	99.101	98.573	98.527	99.057	0.498	0.502	0.223	0.618
7	99.575	99.697	99.286	98.753	98.754	99.213	0.445	0.449	0.199	0.553
8	99.606	99.760	99.401	98.959	98.924	99.330	0.377	0.380	0.169	0.468
9	99.596	99.823	99.500	99.113	99.283	99.463	0.276	0.277	0.123	0.342
10	99.646	99.861	99.543	99.254	99.349	99.531	0.241	0.242	0.108	0.299

Table 8: The removal, F (%), of tarry Shell crude contaminant from duck feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 27.5°C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	69.182	74.045	66.157	75.478	59.558	68.884	6.415	9.313	2.869	7.964
2	84.747	95.939	76.078	96.174	89.483	88.484	8.420	9.516	3.766	10.453
3	96.683	98.812	85.447	98.708	98.131	95.556	5.715	5.981	2.556	7.095
4	97.934	99.434	91.321	99.319	99.157	97.433	3.469	3.560	1.551	4.307
5	98.545	99.544	95.492	99.526	99.274	98.476	1.717	1.743	0.768	2.131
6	99.130	99.599	97.802	99.569	99.380	99.096	0.747	0.754	0.334	0.928
7	99.293	99.682	98.577	99.638	99.458	99.330	0.448	0.451	0.200	0.556
8	99.402	99.710	98.972	99.690	99.477	99.450	0.299	0.300	0.134	0.371
9	99.456	99.765	99.112	99.707	99.506	99.509	0.257	0.259	0.115	0.319
10	99.538	99.751	99.211	99.698	99.535	99.547	0.211	0.212	0.094	0.262

Table 9: The removal, F (%), of tarry Shell crude contamination from duck feather clusters, using the optimal iron powder grade - MH300.29, for the ambient temperatures above the acute temperature for all treatments. Experiments were conducted in five replicates.

At 15.5 °C		At 17.3 °C		At 22.4 °C		At 25.5 °C		At 27.5 °C		At 20.2 °C	
F (%)	CV (%)	**F (%)**	CV (%)	**F (%)**	CV (%)	**F (%)**	CV (%)	**F (%)**	CV (%)	**F (%)**	CV (%)
12.000	15.456	26.471	8.939	66.103	15.064	67.851	11.609	68.884	9.313	59.119	14.119
35.953	17.789	50.931	12.551	83.433	5.924	88.107	9.117	88.484	9.516	79.779	15.324
53.400	13.535	68.900	12.831	92.662	6.440	94.408	6.655	95.556	5.981	91.174	10.528

67.600	12.597	84.175	7.906	96.834	2.592	97.550	2.580	97.433	3.560	96.772	3.545
80.000	**5.040**	**92.741**	**4.923**	**98.432**	**0.780**	**98.764**	**0.809**	**98.476**	**1.743**	**98.727**	**1.082**
86.800	7.807	95.361	4.341	99.036	0.436	99.057	0.502	99.096	0.754	99.282	0.503
91.772	4.294	97.111	2.147	99.243	0.376	99.213	0.449	99.330	0.451	99.493	0.339
95.729	1.155	98.184	0.917	99.304	0.338	99.330	0.380	99.450	0.300	99.561	0.305
97.104	0.705	98.573	0.710	99.389	0.281	99.463	0.277	99.509	0.259	99.638	0.239
97.948	**0.257**	**98.835**	**0.587**	**99.431**	**0.263**	**99.531**	**0.242**	**99.547**	**0.212**	**99.651**	**0.222**

Table 10: Readings of the temperatures of the experiments on penguin feather clusters

T1 (^oC)	T2 (^oC)	T3 (^oC)	T(mean) (^oC)	S	%CV	SE	95%
10.7	11.3	11.1	11.0	0.3	2.8	0.2	0.8
12.1	12.3	12.2	12.2	0.1	0.8	0.1	0.2
14.3	13.7	13.9	14.0	0.3	2.2	0.2	0.8
15.1	14.6	15.2	15.0	0.3	2.1	0.2	0.8
16.7	16.1	15.9	16.2	0.4	2.6	0.2	1.0
18.2	18.4	18.9	18.5	0.4	1.9	0.2	0.9
23.0	22.8	23.3	23.0	0.3	1.1	0.1	0.6
26.7	27.3	27.0	27.0	0.3	1.1	0.2	0.7

Table 11: The removal, F (%), of tarry Shell crude contaminant from penguin feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted one time only at different ambient temperatures for all treatments.

	Oil removal (F%)						
Ambient temp (^oC)	1 treatment	2 treatments	3 treatments	4 treatments	5 treatments	6 treatments	7 treatments
11.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.2	11.23	31.93	57.81	81.67	86.32	89.04	90.53
18.5	13.26	43.16	76.44	85.05	88.77	89.70	91.81
23.0	52.32	78.72	87.88	89.37	90.27	91.36	93.35
27.0	57.85	80.09	89.42	93.00	95.33	95.96	96.58

Table 11 (Cont.): The removal, F (%), of tarry Shell Crude contaminant from penguin feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted one time only at different ambient temperatures for all treatments

	Oil removal F(%)						
Ambient temp	8 treatments	9 treatments	10 treatments	11 treatments	12 treatments	13 treatments	14 treatments

(°C)							
11.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16.2	92.46	93.42	94.21	94.82	95.26	95.70	96.14
18.5	92.82	93.33	94.26	95.02	95.78	96.37	96.88
23.0	95.03	95.73	96.33	96.52	96.43	96.62	97.02
27.0	96.89	97.20	97.36	97.51	97.51	97.82	97.67

Table 12: The removal, F (%), of tarry Shell crude contamination from penguin feather clusters, using the optimal iron powder grade - MH300.29, for different temperatures. Experiments were conducted one time only.

N	Oil removal (F%)							
	At 11 °C	At 12.2 °C	At 14°C	At 15°C	At 16.2°C	At 18.5°C	At 23°C	At 27°C
1	0	0	0	0	11.23	13.26	52.23	57.85
2	0	0	0	0	31.93	43.16	78.75	80.09
3	0	0	0	0	57.81	76.44	87.88	89.42
4	0	0	0	0	81.67	85.05	89.37	93.00
5	0	0	0	0	86.32	88.77	90.27	95.33
6	0	0	0	0	89.04	89.70	91.36	95.96
7	0	0	0	0	90.53	91.81	93.35	96.58
8	0	0	0	0	92.46	92.82	95.03	96.89
9	0	0	0	0	93.42	93.33	95.73	97.20
10	0	0	0	0	94.21	94.26	96.33	97.36
11	0	0	0	0	94.82	95.02	96.52	97.51
12	0	0	0	0	95.26	95.78	96.43	97.51
13	0	0	0	0	95.70	96.37	96.62	97.82
14	0	0	0	0	96.14	96.88	97.02	97.67

Table 13: Comparison between duck and penguin feather clusters for the removal of tarry Shell crude oil, using the optimal iron powder grade - MH300.29, for the final treatment (N= 10 treatments for duck feathers, and N = 14 treatments for penguin feathers).

Duck feathers			Penguin feathers	
Ambient temp (°C)	F%	95%	Ambient temp (°C)	F%
11.0	0	0	11.0	0.00
12.2	0.000	0.000	12.2	0.00
14.0	0.000	0.000	14.0	0.00
15.5	97.948	0.312	15.0	0.00

17.3	98.835	0.720	16.2	96.14
20.2	99.651	0.274	18.5	96.88
22.4	99.431	0.325	23.0	97.02
25.5	99.531	0.299	27.0	97.67
27.5	99.547	0.262		

Table 14: Readings of the temperatures of the experiments on penguin plumage feathers

T1 (^oC)	T2 (^oC)	T3 (^oC)	T(mean) (^oC)	S	%CV	SE	95%
10.0	10.2	9.8	10.0	0.2	2.0	0.1	0.5
11.8	12.3	11.9	12.0	0.3	2.2	0.2	0.7
13.7	14.3	14.0	14.0	0.3	2.1	0.2	0.7
15.9	16.7	16.4	16.3	0.4	2.5	0.2	1.0
18.1	18.5	18.7	18.4	0.3	1.7	0.2	0.8
19.8	20.0	20.5	20.1	0.4	1.8	0.2	0.9
22.1	22.4	22.7	22.4	0.3	1.3	0.2	0.7
23.9	24.5	24.3	24.2	0.3	1.3	0.2	0.8
26.1	26.9	26.2	26.4	0.4	1.7	0.3	1.1

Table 15: The removal, C%, of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at different ambient temperatures for all treatments.

Ambient temperature		1 treatment		2 treatments		3 treatments		4 treatments	
T	s	C%	95%	C%	95%	C%	95%	C%	95%
10.0	0.2	0	0	0	0	0	0	0	0
12.0	0.3	0	0	0	0	0	0	0	0
14.0	0.3	0	0	0	0	0	0	0	0
16.3	0.4	6.38	2.41	18.70	4.12	34.699	3.20	45.83	3.81
18.4	0.3	9.337	2.399	23.805	3.241	38.5185	7.328	50.462	6.837
20.1	0.4	12.665	3.112	30.992	4.701	47.966	4.067	59.554	2.708
22.4	0.3	18.737	6.421	41.222	7.322	57.089	6.819	67.829	6.661
24.2	0.3	26.04	6.376	51.22	10.893	66.67	11.595	75.55	8.416
26.4	0.4	40.13	7.73	64.10	4.47	76.57	2.87	81.44	2.58

Table 15 **(cont.)**: The removal, C (%), of tarry Shell crude contamination from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at different ambient temperatures for all treatments.

5 treatments		6 treatments		7 treatments		8 treatments		9 treatments	
C%	95%	C%	95%	C%	95%	C%	95%	C%	95%
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
54.502	4.869	61.463	2.873	67.826	2.617	74.884	2.400	81.233	3.667
62.392	6.033	70.453	6.716	77.839	3.838	82.994	3.193	86.399	3.129
68.834	4.856	75.697	7.663	82.378	4.909	87.086	3.123	91.571	1.937

76.190	7.221	82.349	5.486	86.557	4.162	89.433	3.780	93.083	3.417
81.583	7.343	86.764	4.871	90.045	3.123	92.625	2.078	94.345	2.203
87.228	3.161	90.462	2.436	92.413	2.478	94.923	2.047	95.601	1.965

Table 16: The removal, C (%), of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 16.3 ^{o}C.

N	Five replicates (C%)					C%(mean)	S	%CV	SE	95%
1	5.16	9.59	6.67	5.78	4.70	6.38	1.94	30.42	0.87	2.41
2	21.52	20.55	19.20	15.20	17.00	18.70	2.59	13.83	1.16	3.21
3	39.46	38.81	35.47	29.55	30.20	34.70	4.66	13.44	2.08	5.79
4	49.55	49.47	44.53	42.18	43.40	45.83	3.46	7.56	1.55	4.30
5	58.30	58.90	52.53	52.89	49.89	54.50	3.92	7.20	1.75	4.87
6	63.23	63.49	62.67	59.31	58.61	61.46	2.31	3.77	1.04	2.87
7	69.06	69.41	69.60	65.74	65.32	67.83	2.11	3.11	0.94	2.62
8	75.78	76.07	76.80	72.16	73.60	74.88	1.93	2.58	0.86	2.40
9	80.27	84.25	84.27	77.52	79.87	81.23	2.95	3.64	1.32	3.67

Table 17: The removal, C (%), of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 18.4 ^{o}C.

N	Five replicates (C%)					C%(mean)	S	%CV	SE	95%
1	8.03	10.80	11.90	7.34	8.61	9.34	1.93	20.70	0.86	2.40
2	21.12	28.40	24.59	24.86	20.06	23.81	3.32	13.95	1.49	4.12
3	38.39	42.74	37.41	38.28	35.77	38.52	2.58	6.70	1.15	3.20
4	49.24	54.80	51.63	50.16	46.48	50.46	3.07	6.08	1.37	3.81
5	62.49	69.13	63.98	60.54	55.82	62.39	4.86	7.79	2.17	6.03
6	70.52	78.16	72.41	67.38	63.79	70.45	5.41	7.68	2.42	6.72
7	75.33	81.93	80.14	76.97	74.82	77.84	3.09	3.97	1.38	3.84
8	80.76	83.94	86.99	82.30	80.97	82.99	2.57	3.10	1.15	3.19
9	84.17	85.46	90.21	87.63	84.52	86.40	2.52	2.92	1.13	3.13

Table 18: The removal, C (%), of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 20.1 ^{o}C.

N	Five replicates (C%)					C%(mean)	S	CV	SE	95%
1	9.85	13.88	15.83	13.38	10.38	12.66	2.51	19.79	1.12	3.11
2	24.82	34.07	34.07	30.61	31.39	30.99	3.79	12.22	1.69	4.70
3	43.43	50.79	49.70	50.34	45.57	47.97	3.28	6.83	1.46	4.07
4	57.66	62.30	61.52	58.05	58.23	59.55	2.18	3.66	0.98	2.71

5	66.42	75.24	69.94	65.99	66.58	68.83	3.91	5.68	1.75	4.86
6	75.55	83.91	77.96	66.89	74.18	75.70	6.17	8.15	2.76	7.66
7	82.48	88.17	83.77	78.23	79.24	82.38	3.95	4.80	1.77	4.91
8	86.86	90.69	88.18	84.13	85.57	87.09	2.52	2.89	1.12	3.12
9	90.15	93.22	91.78	89.80	92.91	91.57	1.56	1.70	0.70	1.94

Table 19: The removal, C (%), of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 22.4 ^{o}C.

N	Five replicates (C%)					C%(mean)	S	%CV	SE	95%
1	22.68	13.81	14.33	17.35	25.51	18.74	5.17	27.60	2.31	6.42
2	45.90	32.93	40.07	39.38	47.84	41.22	5.90	14.31	2.64	7.32
3	59.84	50.53	59.28	52.24	63.55	57.09	5.49	9.62	2.46	6.82
4	70.49	65.10	70.36	59.84	73.35	67.83	5.37	7.91	2.40	6.66
5	77.05	72.85	81.92	68.03	81.09	76.19	5.82	7.63	2.60	7.22
6	83.88	80.10	86.97	75.83	84.97	82.35	4.42	5.37	1.98	5.49
7	89.07	85.83	90.07	81.48	86.33	86.56	3.35	3.87	1.50	4.16
8	92.35	88.28	92.83	85.77	87.93	89.43	3.04	3.40	1.36	3.78
9	96.17	94.27	94.63	90.28	90.07	93.08	2.75	2.96	1.23	3.42

Table 20: The removal, C (%), of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 24.2 ^{o}C.

N	Five replicates (C%)					C%(mean)	S	%CV	SE	95%
1	22.68	21.32	23.17	30.13	32.89	26.04	5.14	19.72	2.30	6.38
2	45.90	41.98	47.02	61.05	60.16	51.22	8.77	17.13	3.92	10.89
3	59.84	56.70	63.76	76.32	76.74	66.67	9.34	14.01	4.18	11.59
4	70.49	69.89	71.56	81.84	83.96	75.55	6.78	8.97	3.03	8.42
5	77.05	79.56	75.69	86.58	89.04	81.58	5.91	7.25	2.65	7.34
6	83.88	86.15	82.34	89.74	91.71	86.76	3.92	4.52	1.75	4.87
7	89.07	88.35	87.39	92.37	93.05	90.04	2.52	2.79	1.12	3.12
8	92.35	92.31	90.14	93.95	94.39	92.63	1.67	1.81	0.75	2.08
9	94.81	95.38	91.28	94.53	95.72	94.35	1.77	1.88	0.79	2.20

Table 21: The removal, C (%), of tarry Shell crude contaminant from plumage (Penguin carcass), using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at 26.4 ^{o}C.

N	Five replicates (C%)					C%(mean)	S	%CV	SE	95%
1	33.64	42.24	40.21	49.33	35.25	40.13	6.23	15.51	2.78	7.73

2	60.61	66.95	61.10	68.73	63.11	64.10	3.60	5.61	1.61	4.47
3	77.27	78.45	75.72	78.44	72.95	76.57	2.31	3.02	1.03	2.87
4	80.61	81.03	82.77	84.10	78.69	81.44	2.08	2.55	0.93	2.58
5	83.33	87.93	88.51	90.03	86.34	87.23	2.55	2.92	1.14	3.16
6	87.27	89.94	91.38	92.18	91.53	90.46	1.96	2.17	0.88	2.44
7	89.70	91.09	92.95	94.61	93.72	92.41	2.00	2.16	0.89	2.48
8	93.33	93.10	96.87	95.96	95.36	94.92	1.65	1.74	0.74	2.05
9	94.55	93.39	97.13	96.77	96.17	95.60	1.58	1.66	0.71	1.96

Table 22: The removal, C (%), of tarry Shell crude contaminant from penguin feather plumage, using the optimal iron powder grade - MH300.29, at ambient temperatures above the acute temperature. Experiments were conducted in five replicates for all treatments.

	At 16.3 ^{0} C		At 18.4 ^{0} C		At 20.1 ^{0} C		At 22.4 ^{0} C		At 24.2 ^{0} C		At 26.4 ^{0} C	
N	C (%)	%CV	C (%)	%CV	C (%)	CV	C (%)	%CV	C (%)	%CV	C (%)	%CV
1	6.38	30.42	9.34	20.70	12.66	19.79	18.74	27.60	26.04	19.72	40.13	15.51
2	18.70	13.83	23.81	13.95	30.99	12.22	41.22	14.31	51.22	17.13	64.10	5.61
3	34.70	13.44	38.52	6.70	47.97	6.83	57.09	9.62	66.67	14.01	76.57	3.02
4	45.83	7.56	50.46	6.08	59.55	3.66	67.83	7.91	75.55	8.97	81.44	2.55
5	54.50	7.20	62.39	7.79	68.83	5.68	76.19	7.63	81.58	7.25	87.23	2.92
6	61.46	3.77	70.45	7.68	75.70	8.15	82.35	5.37	86.76	4.52	90.46	2.17
7	67.83	3.11	77.84	3.97	82.38	4.80	86.56	3.87	90.04	2.79	92.41	2.16
8	74.88	2.58	82.99	3.10	87.09	2.89	89.43	3.40	92.63	1.81	94.92	1.74
9	81.23	3.64	86.40	2.92	91.57	1.70	93.08	2.96	94.35	1.88	95.60	1.66

Table 23: Comparison between duck feather cluster, penguin feather cluster and feather plumage for the removal of tarry Shell crude oil, using the optimal iron powder grade - MH300.29, for the final treatments (after 10 treatments for duck feathers, and 14 treatments for penguin feathers and 9 treatments for feather plumage).

Duck feather cluster			Penguin feather cluster		Feather Plumage		
Ambient temp (^oC)	F%	95%	Ambient temp (^oC)	F%	Ambient temp (^oC)	C%	95%
11.0	0	0	11.0	0.00	10	0	0
12.2	0.000	0.000	12.2	0.00	12	0	0
14.0	0.000	0.000	14.0	0.00	14	0	0
15.5	97.948	0.312	15.0	0.00	16.3	81.233	3.667
17.3	98.835	0.720	16.2	96.14	18.4	86.399	3.129
20.2	99.651	0.274	18.5	96.88	20.1	91.571	1.937
22.4	99.431	0.325	23.0	97.02	22.4	93.083	3.417
25.5	99.531	0.299	27.0	97.67	24.2	94.345	2.203
27.5	99.547	0.262			26.4	95.601	1.965

Table 24: Thermodynamic calculation of the process of magnetic tarry oil removal from duck and penguin feather clusters and penguin feather plumage. Mean and SE values are calculated according to Kirkup (1994).

Number of treatments	**Duck feather cluster**		**Penguin feather cluster**		**Penguin feather plumage**	
	$\Delta S°$ **J mol^{-1} K^{-1}**	$\Delta H°$ **kJ mol^{-1}**	$\Delta S°$ **J mol^{-1} K^{-1}**	$\Delta H°$ **kJ mol^{-1}**	$\Delta S°$ **J mol^{-1} K^{-1}**	$\Delta H°$ **kJ mol^{-1}**
1	548.0	161.5	608.0	181.0	529.8	159.9
2	552.0	159.8	536.7	156.8	495.0	147.0
3	607.0	173.9	415.1	118.7	398.4	116.7
4	602.6	170.6	260.1	71.7	363.6	105.3
5	569.7	159.1	264.7	72.3	427.4	123.3
6	557.0	154.2	251.5	68.0	442.0	127.7
7	497.8	135.9	255.0	68.5	429.7	122.3
8	402.5	107.2	239.9	63.6	443.2	125.4
9	361.6	94.6	240.1	63.3	408.3	114.4
10	320.4	82.1	224.4	58.4		
11			206.7	52.9		
12			172.3	42.7		
13			172.4	42.4		
14			132.7	30.5		
Mean	501.9 ± 32.7	139.9 ± 10.5	284.3 ± 37.1	77.9 ± 11.7	437.5 ± 16.6	126.9 ± 5.6

Table 25: Thermodynamic calculation of the process of magnetic tarry oil removal from duck feather clusters. SE is calculated according to Equations 6.12-6.14 (Kirkup, 1994).

N	$\Delta S°$ **J mol^{-1} K^{-1}**	SE (entropy)	$\Delta H°$ **kJ mol^{-1}**	SE (enthalpy)
1	548.040	135.78	161.484	39.96
2	552.023	96.03	159.837	28.26
3	606.973	108.09	173.889	31.83
4	602.591	153.49	170.621	45.16
5	569.724	184.83	159.139	54.40
6	556.970	192.15	154.200	56.55
7	497.762	182.59	135.942	53.74
8	402.445	145.50	107.165	42.83
9	361.605	134.53	94.610	39.60
10	320.381	113.74	82.116	33.47

Table 26: Thermodynamic calculation of the process of magnetic tarry oil removal from penguin feather clusters. SE is calculated according to Equations 6.12-6.14 (Kirkup, 1994).

N	$\Delta H°$ kJ mol^{-1}	SE (enthalpy)	$\Delta S°$ J mol^{-1} K^{-1}	SE (entropy)
1	180.980	40.37	607.970	137.28
2	156.840	35.44	536.720	120.52
3	118.670	29.68	415.140	100.93
4	71.650	3.25	260.140	11.04
5	72.260	18.33	264.720	62.34
6	67.970	20.93	251.450	71.17
7	68.490	15.19	255.010	51.67
8	63.550	9.17	239.870	31.19
9	63.320	10.52	240.130	35.76
10	58.390	8.12	224.420	27.62
11	52.920	6.33	206.650	21.52
12	42.690	6.56	172.340	22.29
13	42.440	10.44	172.430	35.47
14	30.540	6.81	132.680	23.14

Table 27: Thermodynamic calculation of the process of magnetic tarry oil removal from plumage. SE is calculated according to Equations 6.12-6.14 (Kirkup, 1994).

N	$\Delta S°$ J mol^{-1} K^{-1}	SE (Entropy)	$\Delta H°$ kJ mol^{-1}	SE (enthalpy)
1	529.748	24.89	159.879	7.33
2	495.010	20.94	146.950	6.16
3	398.355	37.06	116.652	10.91
4	363.550	27.04	105.344	7.95
5	427.405	11.15	123.304	3.28
6	441.972	4.79	127.730	1.41
7	429.670	18.59	122.314	5.47
8	443.153	21.79	125.432	6.41
9	408.260	37.49	114.349	11.03

Table 28: Gibbs free energy, ΔG°, calculation of the process of magnetic tarry oil removal from duck feather clusters

	1 treatment		2 treatments		3 treatments		4 treatments		5 treatments	
T (K)	Free energy	Error (FE)	Free energy	Error (FE)	Free energy	Error (FE)	Free energy	Error (FE)	Free energy	Error (FE)
288.5	3.374	1.671	0.579	0.203	-1.223	-0.442	-3.226	-1.676	-5.226	-3.482
290.3	2.388	1.182	-0.415	-0.146	-2.315	-0.836	-4.311	-2.239	-6.252	-4.166
293.2	0.798	0.395	-2.016	-0.707	-4.076	-1.472	-6.059	-3.147	-7.904	-5.266
295.4	-0.407	-0.202	-3.230	-1.133	-5.411	-1.954	-7.384	-3.835	-9.158	-6.102
298.5	-2.106	-1.043	-4.941	-1.733	-7.293	-2.633	-9.252	-4.806	-10.924	-7.278
300.5	-3.202	-1.586	-6.045	-2.121	-8.507	-3.072	-10.457	-5.432	-12.063	-8.038

Table 28 (cont.): Gibbs free energy calculation of the process of magnetic tarry oil removal from duck feather clusters

6 treatments		7 treatments		8 treatments		9 treatments		10 treatments	
Free energy	Error (FE)	Free energy	Error (FE)	Free energy	Error (FE)	Free energy	Error (FE)	Free energy	Error (FE)
-6.486	-4.616	-7.663	-5.840	-8.940	-6.805	-9.713	-7.678	-10.314	-7.865
-7.488	-5.329	-8.559	-6.523	-9.665	-7.357	-10.363	-8.193	-10.891	-8.305
-9.103	-6.479	-10.002	-7.623	-10.832	-8.245	-11.412	-9.022	-11.820	-9.014
-10.329	-7.351	-11.097	-8.458	-11.717	-8.919	-12.208	-9.651	-12.524	-9.551
-12.055	-8.580	-12.640	-9.634	-12.965	-9.869	-13.329	-10.537	-13.518	-10.309
-13.169	-9.373	-13.636	-10.392	-13.770	-10.481	-14.052	-11.109	-14.158	-10.797

Table 29: Gibbs free energy calculation of the process of magnetic tarry oil removal from penguin feathers clusters

	1 treatment		2 treatments		3 treatments		4 treatments		5 treatments		6 treatments		7 treatments	
T (K)	Free energy	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE
289.2	5.155	2.314	1.621	0.730	-1.388	-0.685	-3.582	-0.315	-4.297	-2.102	-4.749	-2.807	-5.259	-2.232
291.5	3.757	1.686	0.386	0.174	-2.343	-1.156	-4.181	-0.367	-4.906	-2.400	-5.328	-3.148	-5.845	-2.481
296.0	1.021	0.458	-2.029	-0.914	-4.211	-2.077	-5.351	-0.470	-6.097	-2.982	-6.459	-3.817	-6.993	-2.968
300.0	-1.411	-0.633	-4.176	-1.881	-5.872	-2.896	-6.392	-0.561	-7.156	-3.500	-7.465	-4.412	-8.013	-3.401

Table 29 (Cont,): Gibbs free energy calculation of the process of magnetic tarry oil removal from penguin feather clusters

8 treatments		9 treatments		10 treatments		11 treatments		12 treatments		13 treatments		14 treatments	
Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE	Free energy(kJ/mol)	SE
-5.820	-1.597	-6.126	-1.930	-6.512	-1.707	-6.843	-1.531	-7.151	-2.024	-7.427	-3.355	-7.831	-3.112
-6.372	-1.748	-6.678	-2.104	-7.028	-1.842	-7.318	-1.638	-7.547	-2.136	-7.823	-3.534	-8.136	-3.233
-7.452	-2.044	-7.758	-2.444	-8.038	-2.107	-8.248	-1.846	-8.323	-2.355	-8.599	-3.884	-8.733	-3.471
-8.411	-2.307	-8.719	-2.747	-8.936	-2.342	-9.075	-2.031	-9.012	-2.550	-9.289	-4.196	-9.264	-3.681

Table 30: Gibbs free energy calculation of the process of magnetic tarry oil removal from plumage

	1 treatment		2 treatments		3 treatments		4 treatments		5 treatments		6 treatments		7 treatments		8 treatments		9 treatments	
T (K)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)	Free energy	Error (SE)
289.3	6.62	0.61	3.74	0.32	1.41	0.26	0.17	0.03	-0.34	-0.02	-0.13	0.00	-1.99	-0.18	-2.77	-0.28	-3.76	-0.71
291.4	5.51	0.51	2.70	0.23	0.57	0.11	-0.59	-0.09	-1.24	-0.07	-1.06	-0.02	-2.89	-0.25	-3.70	-0.37	-4.62	-0.87
293.1	4.61	0.43	1.86	0.16	-0.11	-0.02	-1.21	-0.18	-1.97	-0.10	-1.81	-0.04	-3.62	-0.32	-4.46	-0.45	-5.31	-1.00
295.4	3.39	0.31	0.72	0.06	-1.02	-0.19	-2.05	-0.31	-2.95	-0.16	-2.83	-0.06	-4.61	-0.41	-5.48	-0.55	-6.25	-1.18
297.2	2.44	0.23	-0.17	-0.01	-1.74	-0.32	-2.70	-0.41	-3.72	-0.20	-3.62	-0.08	-5.38	-0.47	-6.27	-0.63	-6.99	-1.32
299.4	1.27	0.12	-1.26	-0.11	-2.62	-0.49	-3.50	-0.53	-4.66	-0.25	-4.60	-0.10	-6.33	-0.56	-7.25	-0.73	-7.88	-1.48

Van’t hoff plots for the magnetic tarry oil removal from duck feather clusters for all treatments

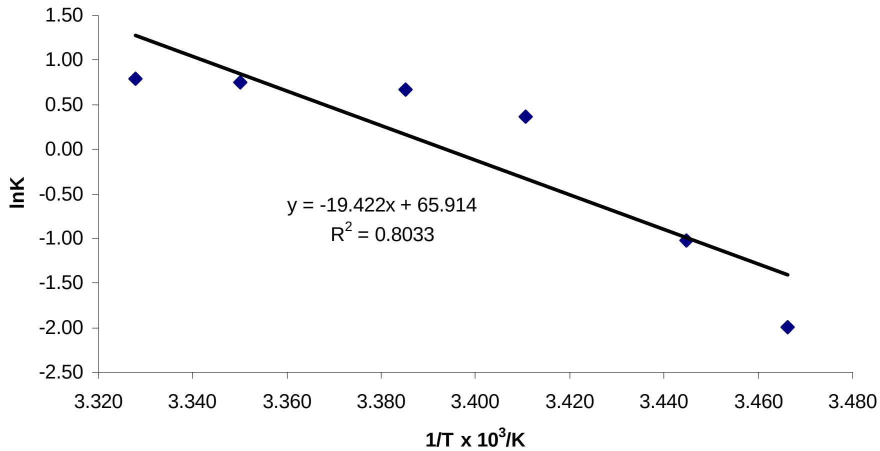


Figure 1: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (1 treatment)

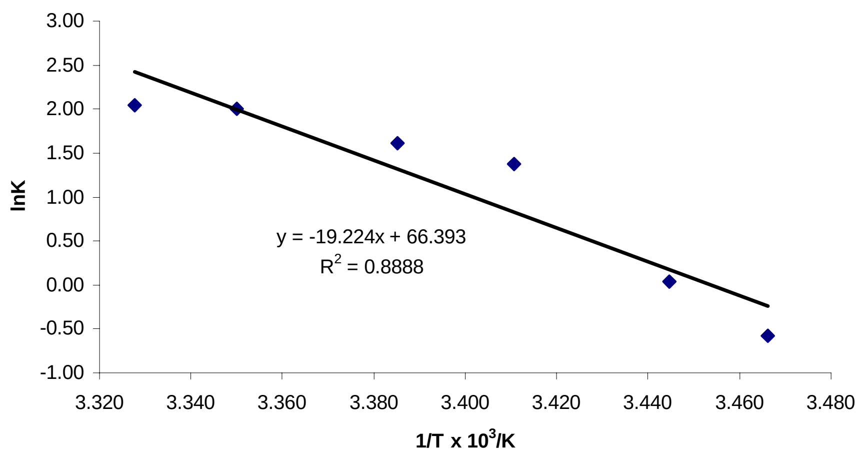


Figure 2: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (2 treatments)

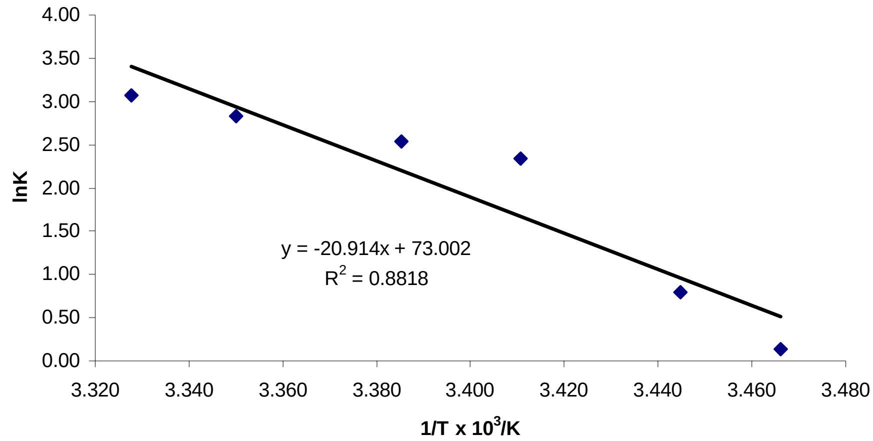


Figure 3: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (3 treatments)

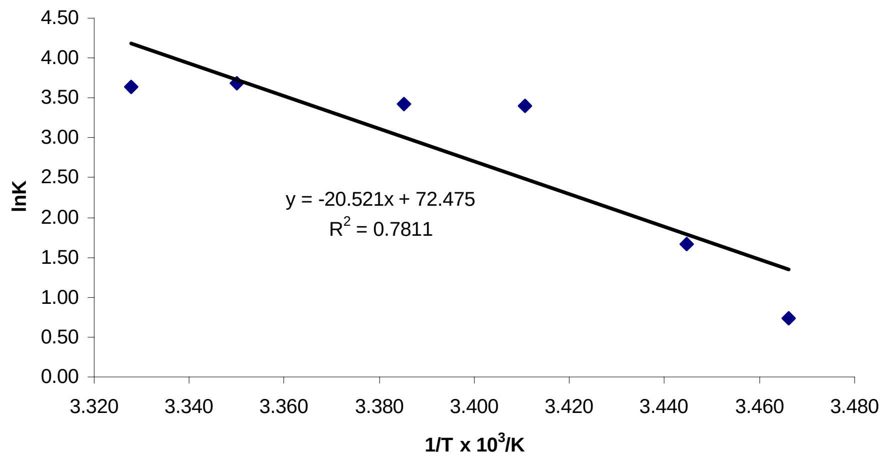


Figure 4: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (4 treatments)

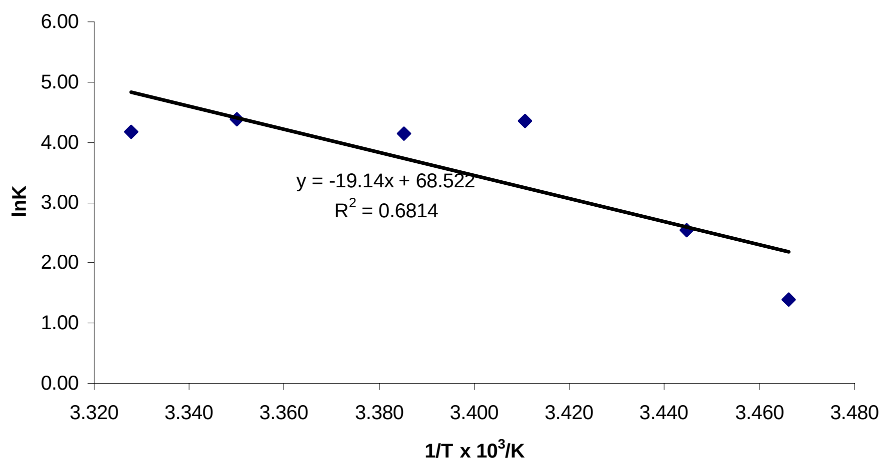


Figure 5: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (5 treatments)

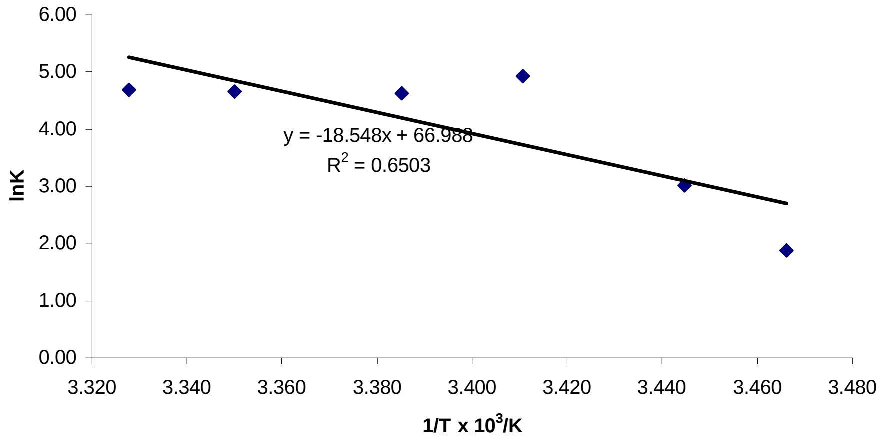


Figure 6: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (6 treatments)

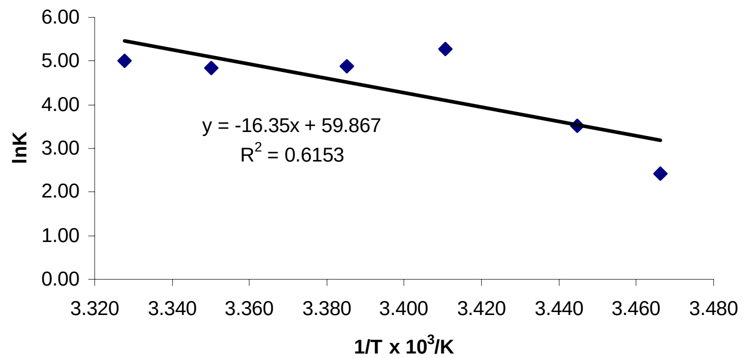


Figure 7: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (7 treatments)

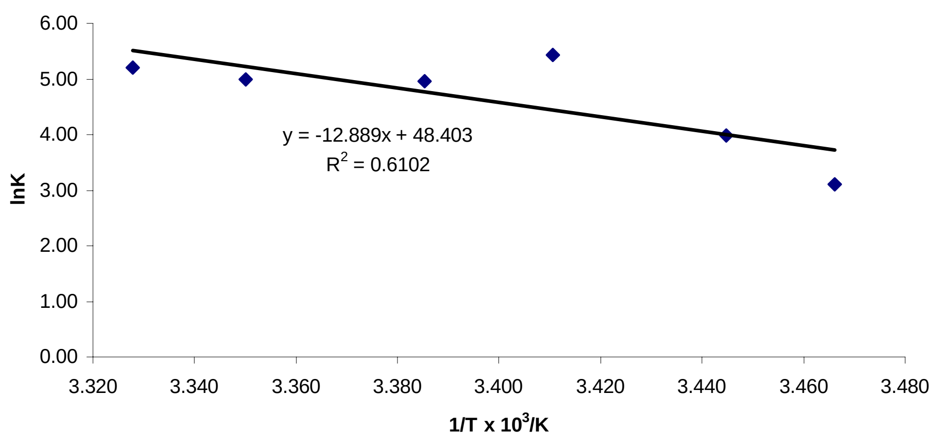


Figure 8: The van’t Hoff plot for the sorption of tarry oil from duck feather cluster (8 treatments)

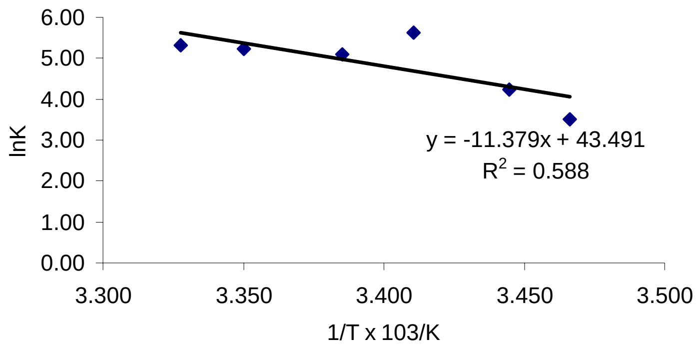


Figure 9: The van't Hoff plot for the sorption of tarry oil from duck feather cluster (9 treatments)

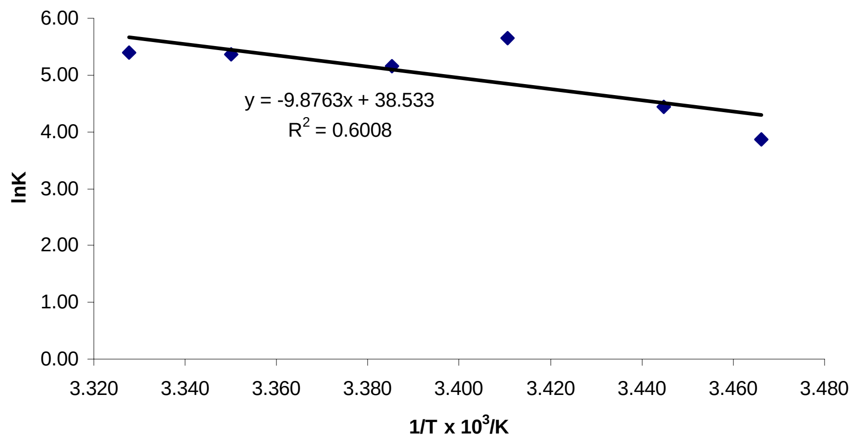


Figure 10: The van't Hoff plot for the sorption of tarry oil from duck feather cluster (10 treatments)

Van't hoff plots for the magnetic tarry oil removal from penguin feather clusters for all treatments

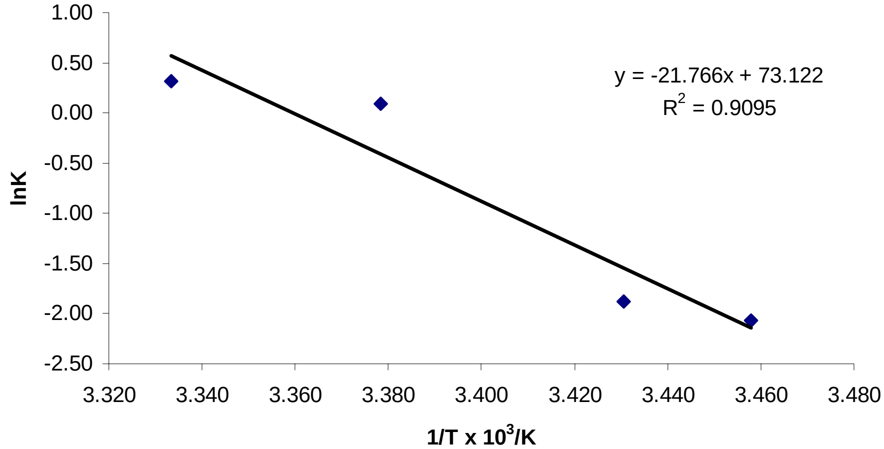


Figure 11: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (1 treatment)

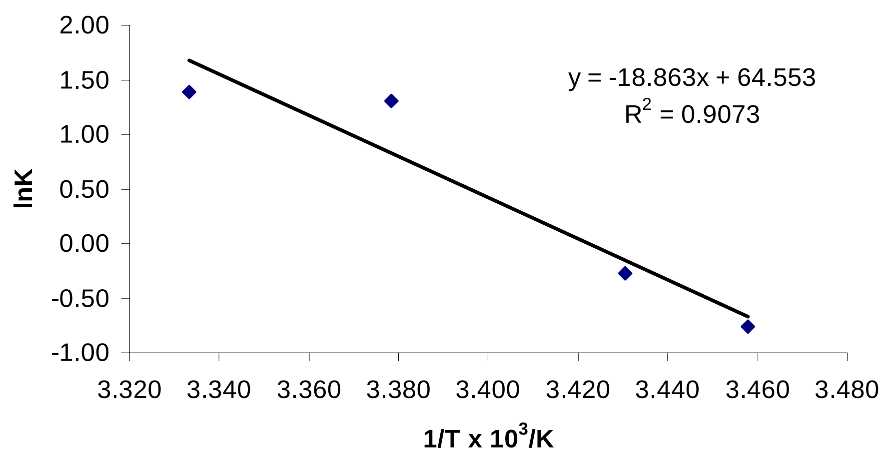


Figure 12: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (2 treatments)

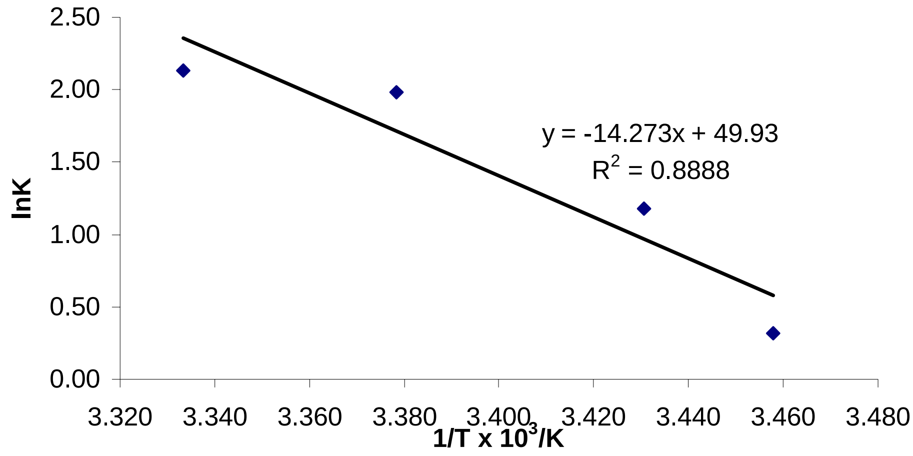


Figure 13: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (3 treatments)

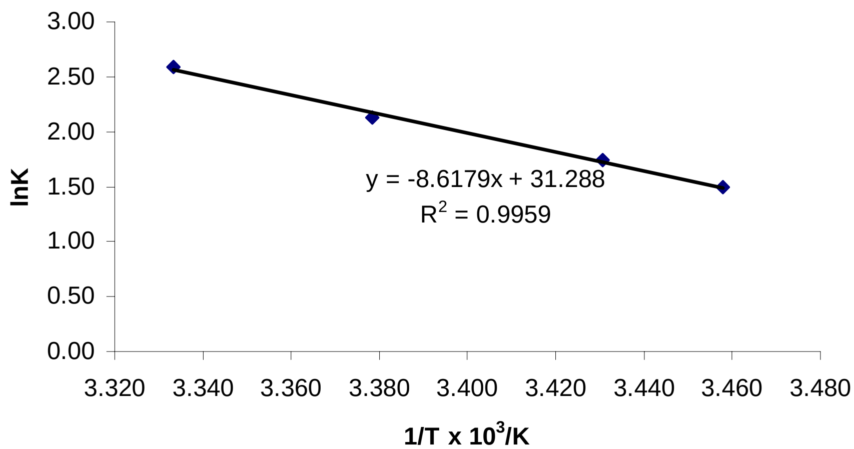


Figure 14: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (4 treatments)

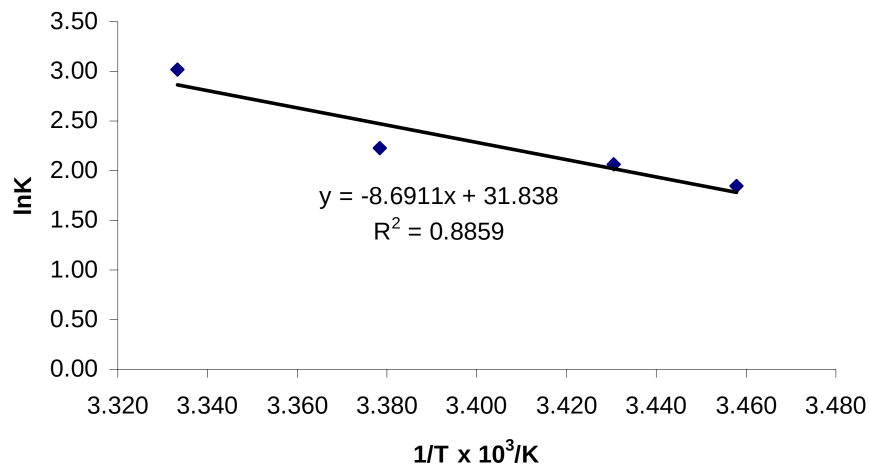


Figure 15: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (5 treatments)

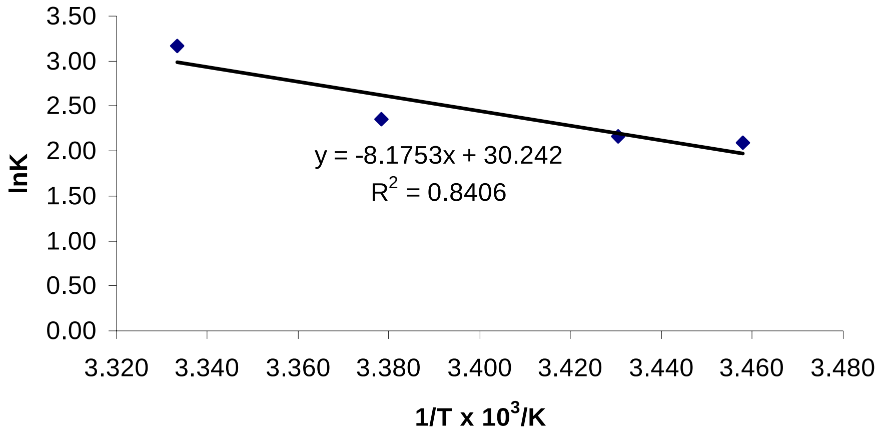


Figure 16: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (6 treatments)

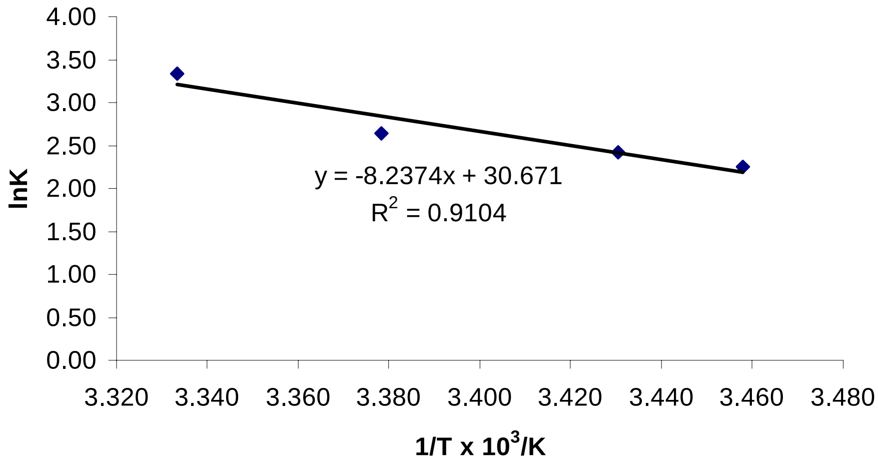


Figure 17: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (7 treatments)

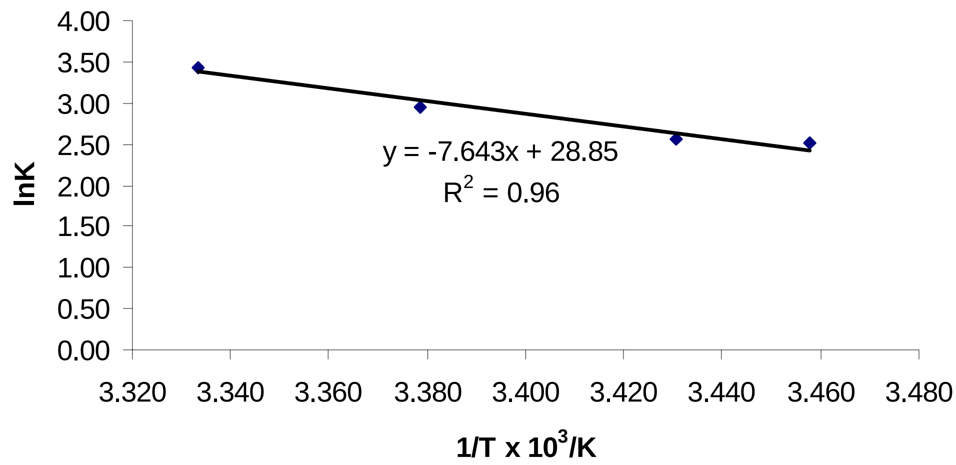


Figure 18: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (8 treatments)

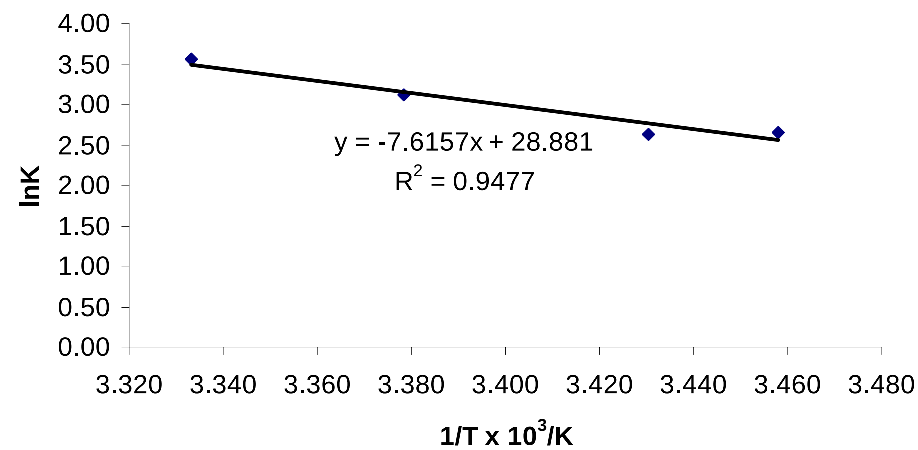


Figure 19: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (9 treatments)

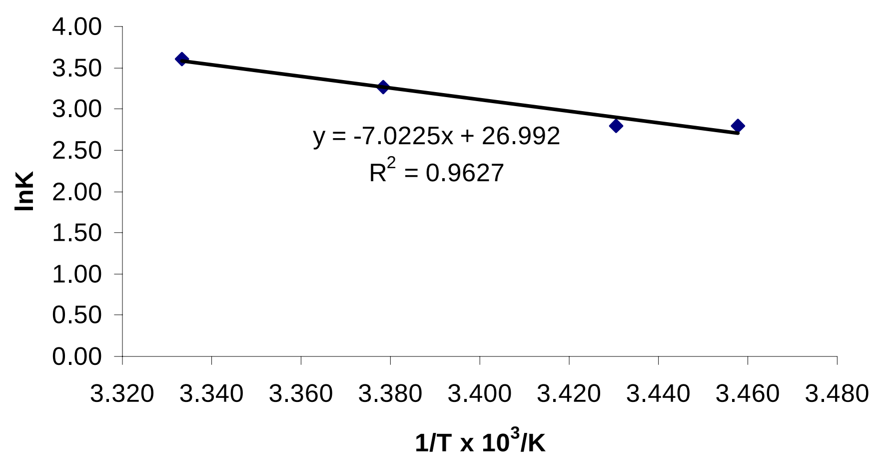


Figure 20: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (10 treatments)

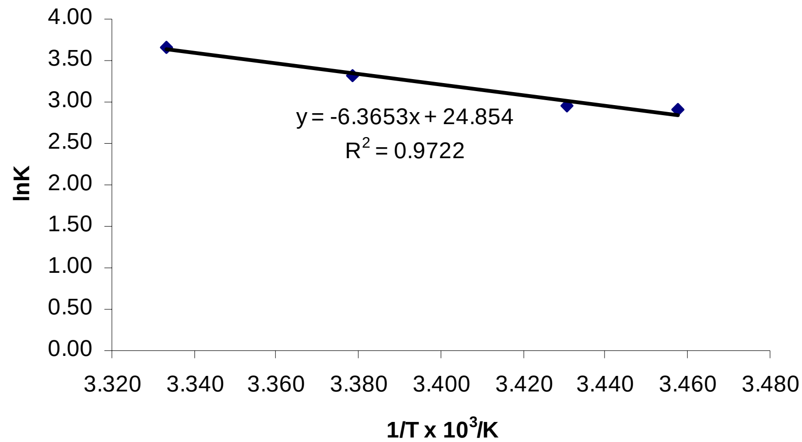


Figure 21: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (11 treatments)

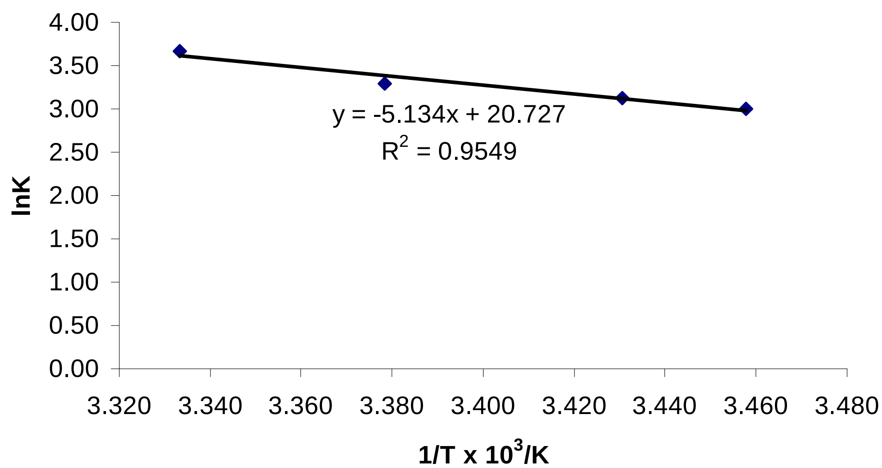


Figure 22: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (12 treatments)

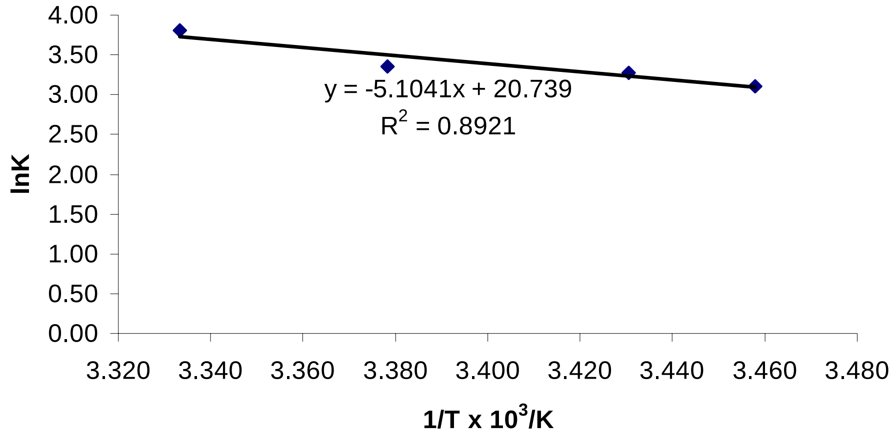


Figure 23: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (13 treatments)

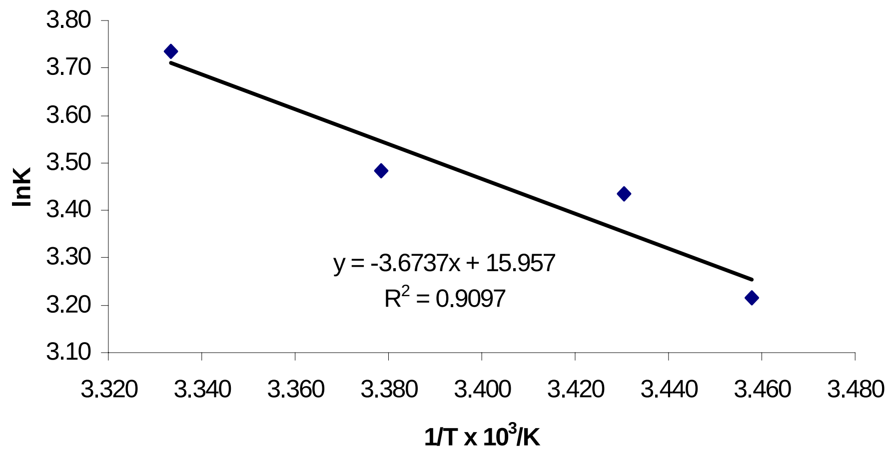


Figure 24: The van't Hoff plot for the sorption of tarry oil from penguin feather cluster (14 treatments)

Van't hoff plots for the magnetic tarry oil removal from penguin feather plumage for all treatments

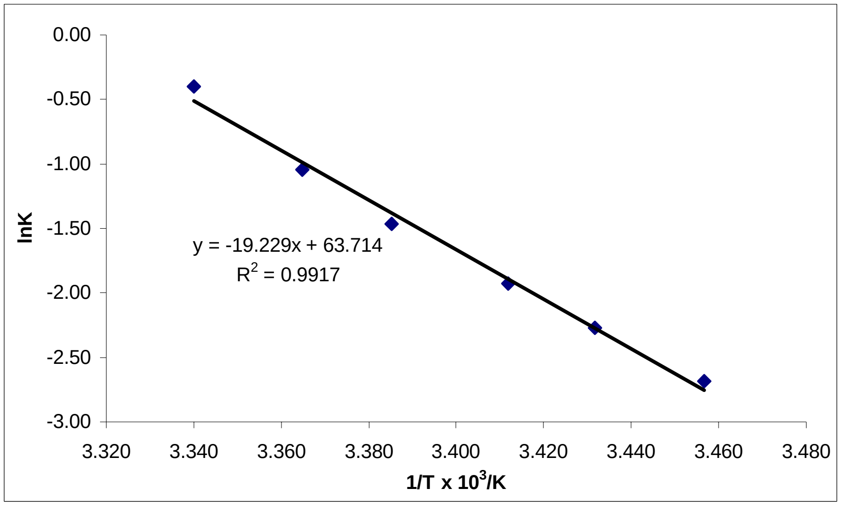


Figure 25: The van't Hoff plot for the sorption of tarry oil from penguin feather plumage (1 treatment)

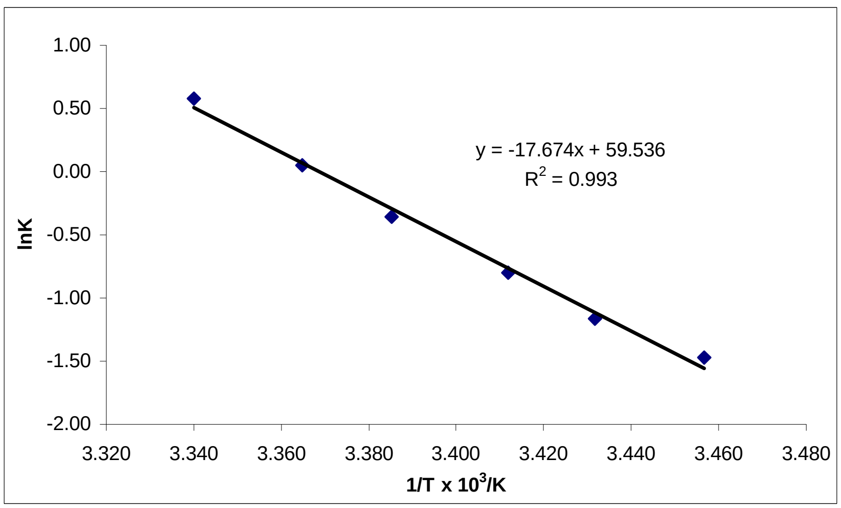


Figure 26: The van't Hoff plot for the sorption of tarry oil from penguin feather plumage (2 treatments)

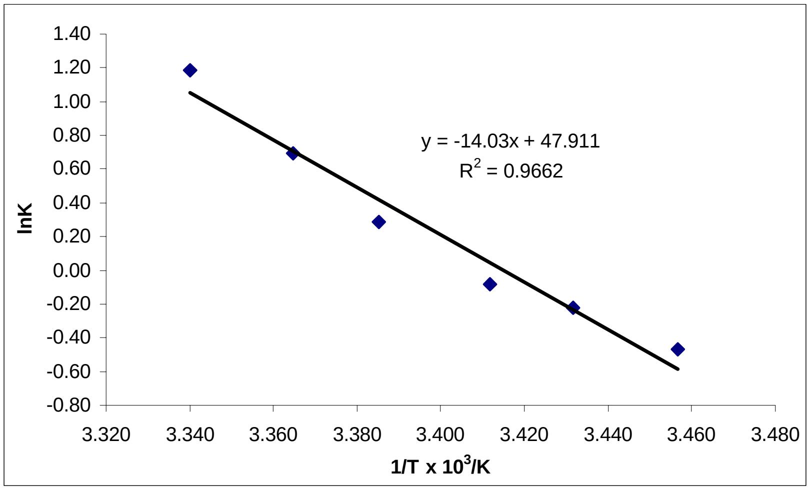


Figure 27: The van’t Hoff plot for the sorption of tarry oil from penguin feather plumage (3 treatments)

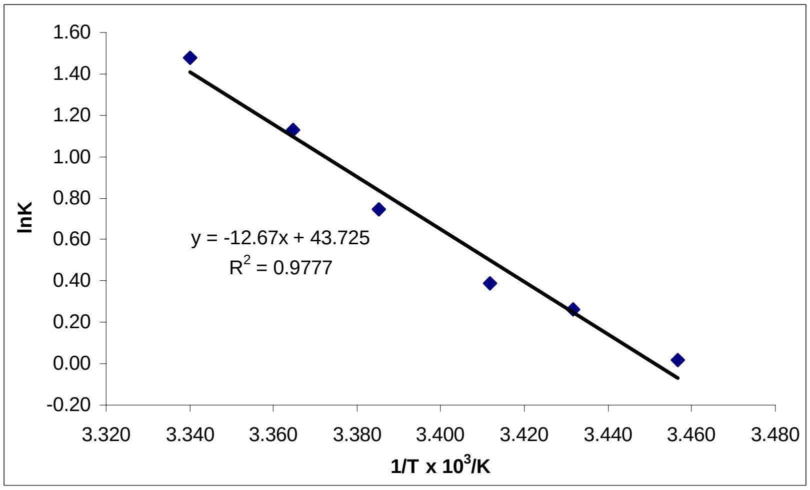


Figure 28: The van’t Hoff plot for the sorption of tarry oil from penguin feather plumage (4 treatments)

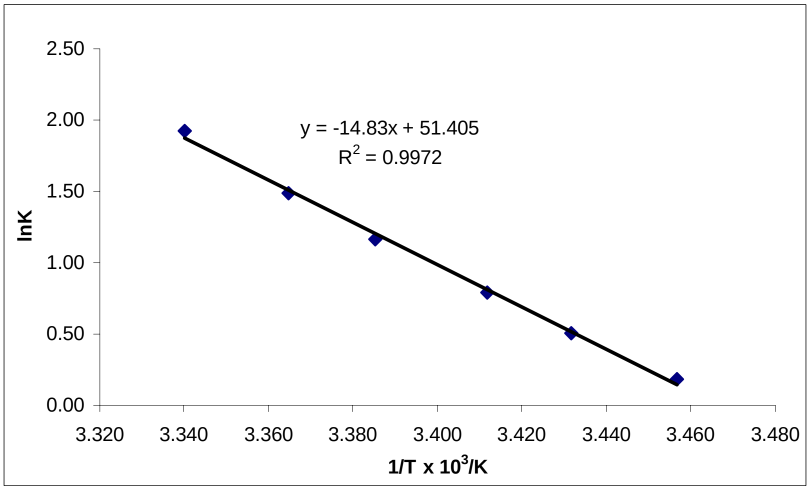


Figure 29: The van't Hoff plot for the sorption of tarry oil from penguin feather plumage (5 treatments)

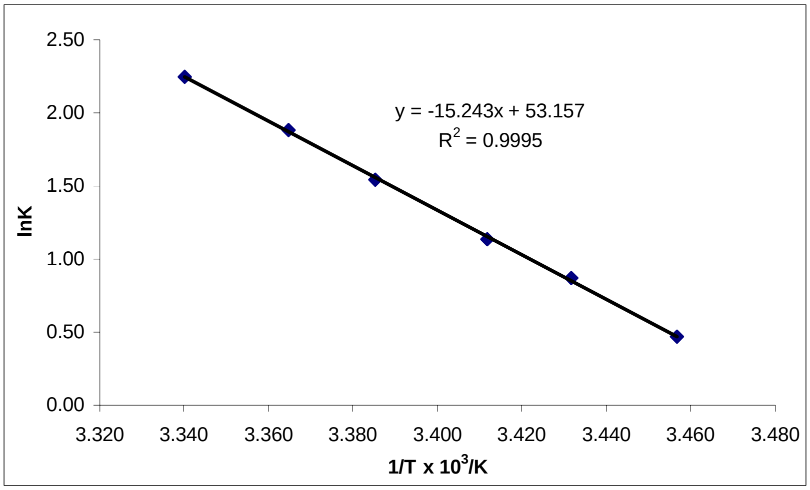


Figure 30: The van't Hoff plot for the sorption of tarry oil from penguin feather plumage (6 treatments)

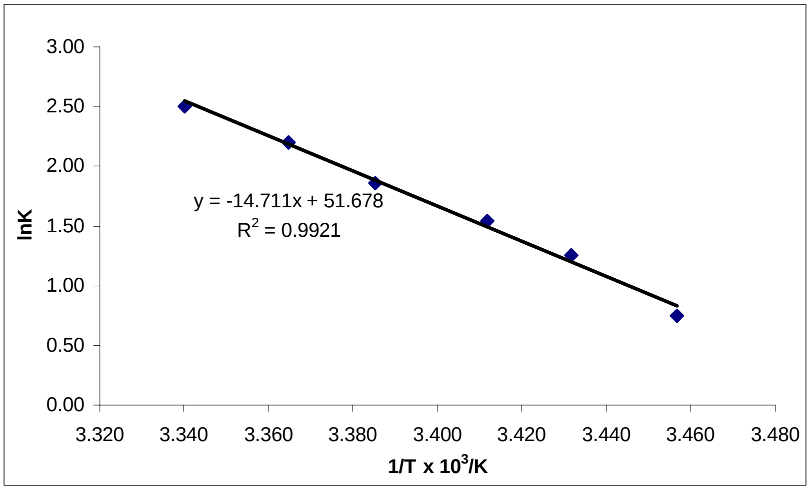


Figure 5.31: The van't Hoff plot for the sorption of tarry oil from penguin feather plumage (7 treatments)

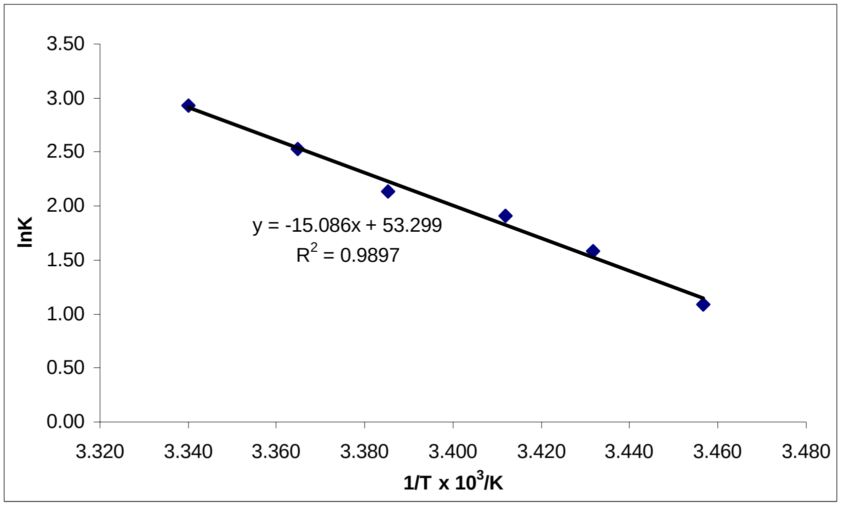


Figure 32: The van’t Hoff plot for the sorption of tarry oil from penguin feather plumage (8 treatments)

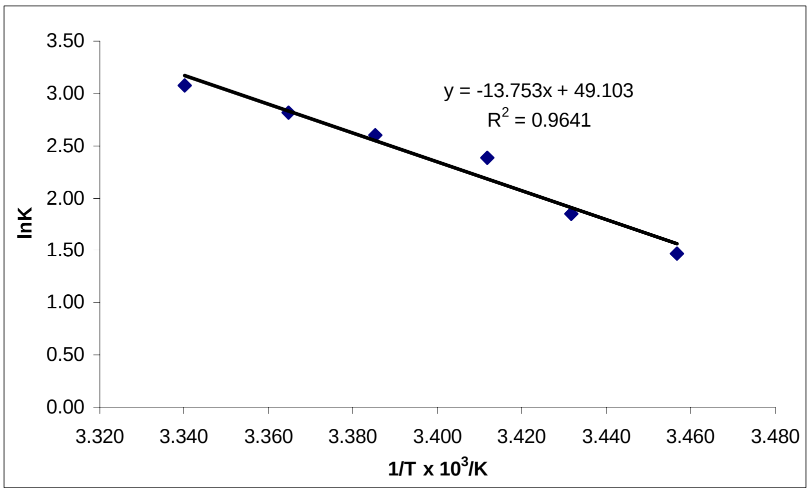


Figure 33: The van’t Hoff plot for the sorption of tarry oil from penguin feather plumage (9 treatments)

Appendix 5.2

Calculation Sample 1: Assume that 10 g oil with 5 components; component 1: 3g, component 2: 3g, component 3: 2 g, component 4: 1 g, component 5: 1 g, and their molecular weight is 10, 20, 25, 40 and 50, respectively.

Suppose that the percentage of removal (by weight) is 12.7% (N = 1 from Fig.5.6) therefore K_{mass} calculated according to Equation 5.5 will be 0.127/ (1 - 0.127) = 0.145.

Assume that the composition of the oil (mixture) removed from the surface of the tarry deposit onto the iron particles is the same as that in the bulk, as a result, the mass of each component in the oil (mixture) removed will be as follow: component 1: 3 x 12.7% = 0.38 g, component 2: 3 x 12.7% = 0.38 g, component 3: 2 x 12.7% = 0.25 g, component 4: 1 x 12.7% = 0.13 g and component 5: 1 x 12.7% = 0.13 g. Their corresponding mole of each of the components will be: 0.38/10 for component 1; 0.38 / 20 for component 2; 0.25/25 for component 3; 0.13/40 for component 4 and 0.13/50 for component 5. The mole for each of the components in the oil remained in the bulk will be 2.62/10 for component 1; 2.62/20 for component 2; 1.75/25 for component 3; 0.87/40 for component 4 and 0.87/50 for component 5.

Therefore, the K_{mole} of the oil (mixture) removed over the oil in the bulk will be:

[(0.38/10) + (0.38/20) +(0.25/25) + (0.13/40) + (0.13/50)] / [(2.62/10) +(2.62/20) +(1.75/25) + (0.87/40) + (0.87/50)] = 0.145, which is equal to the K_{mass}.

The detail of this calculation sample above is further demonstrated in the table below, Table a.

	10 g oil				
	Component 1	Component 2	Component 3	Component 4	Component 5
Mass	3.00	3.00	2.00	1.00	1.00
Molecular weight	10.00	20.00	25.00	40.00	50.00
oil removed (12.7%)		3 g			
K_{mass}	**=0.127/(1-0.127)= 0.145**				
Oil mixture (removed)- composition the same					
Mass removed	0.38	0.38	0.25	0.13	0.13
Percentage (%)	**12.70**	**12.70**	**12.70**	**12.70**	**12.70**
Molecular weight	10.00	20.00	25.00	40.00	50.00
Mole	0.038	0.019	0.010	0.003	0.003
Total moles	0.073				

Oil on the surface					
Mass	2.62	2.62	1.75	0.87	0.87
Molecular weight	10.00	20.00	25.00	40.00	50.00
Mole	0.26	0.13	0.07	0.02	0.02
Total moles	0.50				
K_{mole}	**=0.073/0.50=0.145**				

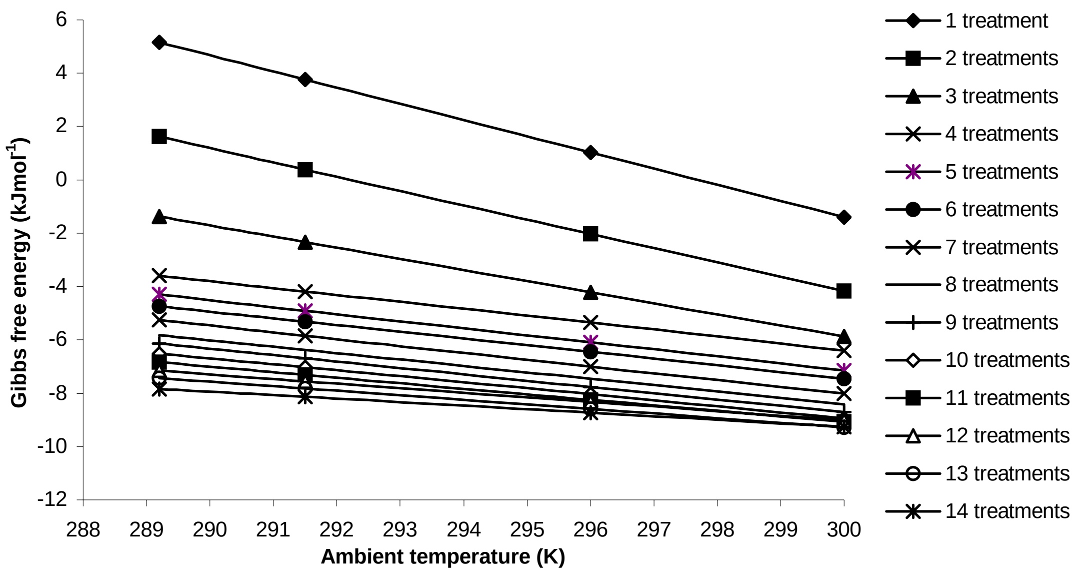


Figure 1: Gibbs free energy of the process of magnetic removal of tarry oil from penguin feather clusters versus ambient temperature for all treatments. Error bars are omitted for clarity. The data are presented in Table 29 in Appendix 5.1.

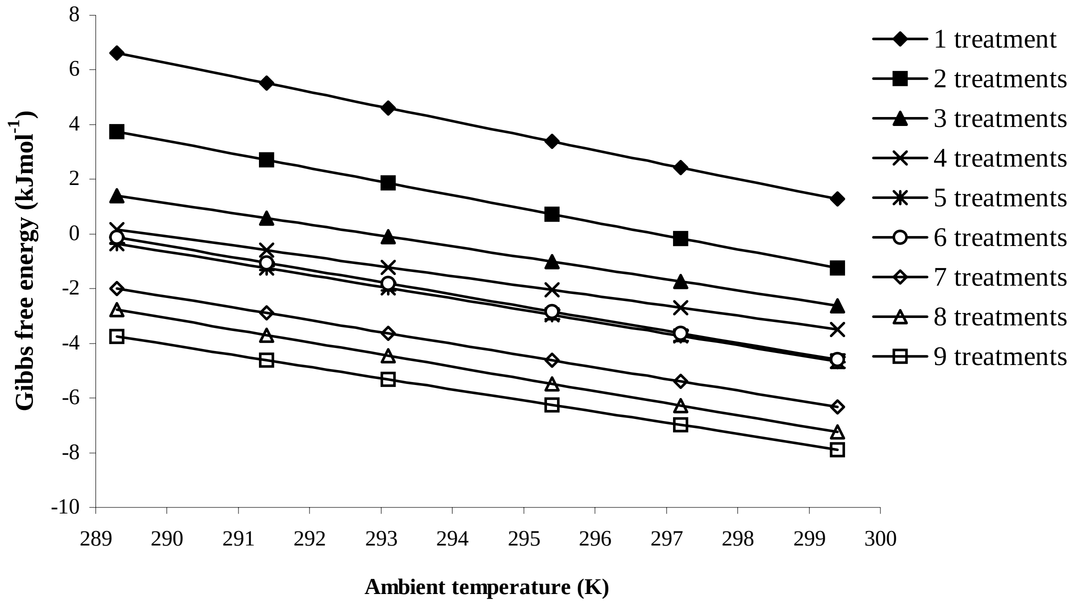


Figure 2: Gibbs free energy of the process of magnetic removal of tarry oil from feather plumage versus ambient temperature for all treatments. Error bars are omitted for clarity. The data are presented in Table 30 in Appendix 5.1.

Appendix 6

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Table 1: Monitoring of loss of the weight of the oiled duck feather clusters over time by evaporation for crude oil (SO) and bunker oil (BO2).

Time of weathering (day)	Bunker oiled duck feather (g)	Time of weathering (day)	Crude oiled duck feather (g)
0	1.256	0	1.966
1	1.205	0.33	1.918
2	1.174	1	1.87
3	1.155	2	1.817
4	1.132	3	1.7690
5	1.121	4	1.7200
6	1.114	5	1.6940
7	1.108	6	1.6720
8	1.104	7	1.6500
9	1.100	8	1.6400
10	1.096	9	1.6310
11	1.092	10	1.616
12	1.089	11	1.605
13	1.086	12	1.6
14	1.083	13	1.59104
		14	1.5857

Table 2: Comparison of crude oil removal from duck feathers, F (%), amongst different times of weathering using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca.22^{o}C

Number of Treatments (N)	1-day weathering		7-day weathering		14-day weathering	
	F%	SE	F%	SE	F%	SE
1	66.103	4.45	37.641	4.34	15.276	2.942
2	83.433	2.21	59.168	3.75	37.930	5.401
3	92.662	2.67	76.595	2.69	58.953	6.246
4	96.834	1.12	83.997	2.58	75.505	7.531
5	98.432	0.34	91.558	1.76	85.056	5.501
6	99.036	0.19	96.157	1.02	92.299	3.211

7	99.243	0.17	97.613	0.54	96.060	2.098
8	99.304	0.15	98.193	0.39	97.456	1.461
9	99.389	0.12	98.788	0.33	98.773	0.366
10	99.431	0.12	99.046	0.21	99.151	0.161
11			99.249	0.14	99.263	0.112
12			99.370	0.12	99.309	0.083
13			99.375	0.10	99.335	0.061
14			99.354	0.10	99.349	0.048

Table 3: The removal, F (%), of one-day weathered crude oil from duck feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates and at ca.22 ^{o}C.

N	**Five replicates (F%)**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	54.97	68.96	72.46	77.60	56.52	66.10	9.96	15.06	4.45	12.36
2	76.18	88.35	85.52	86.44	80.68	83.43	4.94	5.92	2.21	6.14
3	85.16	97.53	97.32	96.05	87.25	92.66	5.97	6.44	2.67	7.41
4	93.23	98.42	99.25	98.01	95.26	96.83	2.51	2.59	1.12	3.12
5	97.55	98.80	99.38	98.69	97.74	98.43	0.77	0.78	0.34	0.95
6	98.39	99.14	99.59	99.09	98.97	99.04	0.43	0.44	0.19	0.54
7	98.74	99.33	99.78	99.20	99.16	99.24	0.37	0.38	0.17	0.46
8	98.81	99.35	99.76	99.31	99.28	99.30	0.34	0.34	0.15	0.42
9	99.03	99.38	99.82	99.36	99.35	99.39	0.28	0.28	0.12	0.35
10	99.09	99.44	99.83	99.41	99.39	99.43	0.26	0.26	0.12	0.32

Table 4: The removal, F (%), of seven-day weathered crude oil from duck feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates and at ca. 22^{o}C.

N	**Five replicates (F%)**					**F%(mean)**	**s**	**%CV**	**SE**	**95%**
1	51.68	24.87	34.20	37.63	39.82	37.64	9.70	25.78	4.34	12.05
2	69.44	48.55	65.62	54.98	57.26	59.17	8.38	14.17	3.75	10.41
3	80.39	73.76	83.25	67.84	77.73	76.59	6.01	7.85	2.69	7.47
4	89.96	84.66	85.94	74.40	85.03	84.00	5.77	6.87	2.58	7.16
5	92.76	93.58	93.09	84.57	93.79	91.56	3.93	4.29	1.76	4.87
6	98.41	96.11	97.54	92.45	96.27	96.16	2.28	2.37	1.02	2.83
7	98.91	97.83	98.15	95.67	97.50	97.61	1.21	1.24	0.54	1.50
8	99.02	98.22	98.77	96.79	98.18	98.19	0.86	0.88	0.39	1.07
9	99.34	99.10	99.24	97.52	98.74	98.79	0.75	0.75	0.33	0.93
10	99.39	99.19	99.40	98.26	98.99	99.05	0.47	0.48	0.21	0.58
11	99.51	99.28	99.46	98.74	99.25	99.25	0.30	0.31	0.14	0.38

12	99.55	99.49	99.55	98.89	99.37	99.37	0.28	0.28	0.12	0.35
13	99.52	99.48	99.56	99.00	99.32	99.37	0.23	0.23	0.10	0.28
14	99.57	99.44	99.50	98.98	99.28	99.35	0.23	0.24	0.10	0.29

Table 5: The removal, F (%), of 14-day weathered crude oil from duck feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates and at ca. 22 ^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	5.554	13.262	14.836	21.723	21.004	15.276	6.579	43.068	2.942	8.168
2	17.830	35.319	45.169	46.150	45.184	37.930	12.077	31.840	5.401	14.993
3	36.407	55.716	62.832	71.705	68.107	58.953	13.967	23.691	6.246	17.339
4	48.001	70.830	83.852	86.336	88.506	75.505	16.840	22.303	7.531	20.906
5	64.504	85.572	86.046	94.877	94.280	85.056	12.300	14.461	5.501	15.270
6	79.922	93.430	93.539	97.594	97.010	92.299	7.180	7.780	3.211	8.914
7	87.724	97.225	98.648	98.428	98.278	96.060	4.692	4.885	2.098	5.825
8	91.656	98.207	99.069	99.129	99.220	97.456	3.268	3.353	1.461	4.057
9	97.415	98.589	99.219	99.380	99.263	98.773	0.819	0.830	0.366	1.017
10	98.669	98.865	99.423	99.450	99.350	99.151	0.359	0.363	0.161	0.446
11	99.087	98.913	99.443	99.492	99.383	99.263	0.251	0.253	0.112	0.312
12	99.195	99.037	99.436	99.472	99.404	99.309	0.186	0.188	0.083	0.231
13	99.226	99.237	99.457	99.509	99.248	99.335	0.136	0.137	0.061	0.169
14	99.250	99.245	99.359	99.502	99.391	99.349	0.107	0.108	0.048	0.133

Table 6: Comparison of crude oil removal from penguin feathers for different times of weathering using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22^{o}C.

N	1-day weathering		7-day weathering		14-day weathering	
	F%	SE	F%	SE	F%	SE
1	56.41	1.99	16.86	2.49	10.80	0.79
2	75.29	3.03	48.81	4.35	42.57	5.52
3	83.80	2.97	75.86	3.07	66.10	6.19
4	89.50	1.74	84.35	2.47	79.62	4.10
5	93.00	1.56	88.02	1.92	86.32	2.62
6	94.65	1.12	90.60	1.59	90.12	2.18
7	95.66	0.82	92.72	0.97	91.47	1.95
8	96.21	0.70	94.11	0.94	92.67	1.86

9	96.61	0.55	94.86	0.76	93.44	1.65
10	96.85	0.51	95.26	0.70	94.45	1.59
11	97.07	0.44	95.82	0.58	95.20	1.29
12	97.32	0.33	96.24	0.50	96.05	0.92
13	97.47	0.33	96.97	1.12	96.70	0.59
14	97.53	0.30	97.21	0.98	96.99	0.46

Table 7: The removal, F (%), of 1-day weathered crude oil from penguin feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates and at ca. 22 ^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	57.85	48.34	49.72	62.82	64.58	56.41	4.445	7.880	1.988	5.518
2	80.09	70.90	64.89	71.96	78.90	75.29	6.779	9.004	3.032	8.416
3	89.42	85.75	74.18	79.64	87.00	83.80	6.637	7.920	2.968	8.240
4	93.00	92.55	83.30	88.73	89.91	89.50	3.895	4.352	1.742	4.836
5	95.33	95.26	86.92	93.47	94.04	93.00	3.493	3.756	1.562	4.337
6	95.96	96.07	90.19	95.77	95.26	94.65	2.513	2.655	1.124	3.120
7	96.58	96.61	92.43	96.67	96.02	95.66	1.827	1.910	0.817	2.269
8	96.89	96.88	93.46	97.31	96.48	96.21	1.563	1.624	0.699	1.940
9	97.20	97.02	94.49	97.57	96.79	96.61	1.220	1.262	0.545	1.514
10	97.36	97.29	94.84	97.70	97.09	96.85	1.149	1.186	0.514	1.426
11	97.51	97.43	95.35	97.82	97.25	97.07	0.984	1.013	0.440	1.221
12	97.51	97.70	96.04	97.95	97.40	97.32	0.745	0.765	0.333	0.925
13	97.82	97.70	96.21	98.08	97.55	97.47	0.730	0.749	0.327	0.907
14	97.46	97.83	96.39	99.02	97.35	97.53	0.669	0.686	0.299	0.830

Table 8: The removal, F (%), of 7-day weathered crude oil from penguin feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates and at ca.22 ^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	0.95
1	14.38	12.60	26.25	13.53	17.57	16.86	5.57	33.01	2.49	6.91
2	44.01	48.04	65.49	45.96	40.57	48.81	9.72	19.91	4.35	12.07

3	72.76	68.72	87.12	76.02	74.68	75.86	6.87	9.06	3.07	8.53
4	82.09	76.54	91.01	87.74	84.37	84.35	5.52	6.55	2.47	6.86
5	86.76	81.98	93.07	91.10	87.21	88.02	4.29	4.88	1.92	5.33
6	89.53	85.34	94.41	93.28	90.44	90.60	3.56	3.92	1.59	4.41
7	91.05	90.08	95.14	94.55	92.76	92.72	2.18	2.35	0.97	2.70
8	92.43	92.04	95.63	96.91	93.54	94.11	2.10	2.23	0.94	2.60
9	93.19	93.99	96.11	97.18	93.80	94.86	1.71	1.80	0.76	2.12
10	93.95	94.41	96.60	97.28	94.06	95.26	1.56	1.64	0.70	1.94
11	94.83	94.83	96.96	97.49	94.97	95.82	1.30	1.36	0.58	1.61
12	95.46	95.25	97.21	97.67	95.62	96.24	1.11	1.16	0.50	1.38
13	96.21	96.39	97.58	98.25	96.41	96.97	0.90	0.93	0.40	1.12
14	96.51	96.58	97.78	98.30	96.87	97.21	0.79	0.82	0.35	0.98

Table 9: The removal, F (%), of 14-day weathered crude oil from penguin feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates and at ca. 22 ^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	11.73	10.86	13.09	8.49	9.83	10.80	1.76	16.29	0.79	2.18
2	35.67	40.22	54.94	27.66	54.37	42.57	11.91	27.98	5.52	14.79
3	64.95	53.08	79.90	52.06	80.53	66.10	13.85	20.95	6.19	17.19
4	80.87	67.33	87.28	73.59	89.03	79.62	9.17	11.51	4.10	11.38
5	88.46	77.40	90.97	83.57	91.22	86.32	5.86	6.79	2.62	7.27
6	92.73	82.66	92.43	87.95	94.85	90.12	4.87	5.40	2.18	6.05
7	93.59	84.54	93.98	89.90	95.32	91.47	4.36	4.77	1.95	5.42
8	95.08	86.15	94.66	91.00	96.47	92.67	4.17	4.50	1.86	5.18
9	95.30	87.63	95.34	92.09	96.85	93.44	3.68	3.94	1.65	4.57
10	96.79	88.71	96.21	93.31	97.23	94.45	3.56	3.77	1.59	4.42
11	97.01	90.45	96.80	94.40	97.33	95.20	2.89	3.04	1.29	3.59
12	97.44	92.74	97.18	95.38	97.52	96.05	2.05	2.13	0.92	2.54
13	97.65	94.49	97.28	96.47	97.61	96.70	1.32	1.37	0.59	1.64
14	97.76	95.16	97.28	97.32	97.42	96.99	1.04	1.07	0.46	1.29

Table 10: Comparison of the pick-up of 1-day weathered crude oil between duck and penguin feather clusters, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates.

	Duck feather		Penguin feather	
N	Oil removed (%)	SE	Oil removed (%)	SE
1	66.103	4.45	56.41	1.99
2	83.433	2.21	75.29	3.03
3	92.662	2.67	83.80	2.97
4	96.834	1.12	89.50	1.74
5	98.432	0.34	93.00	1.56
6	99.036	0.19	94.65	1.12
7	99.243	0.17	95.66	0.82
8	99.304	0.15	96.21	0.70
9	99.389	0.12	96.61	0.55
10	99.431	0.12	96.85	0.51
11			97.07	0.44
12			97.32	0.33
13			97.47	0.33
14			97.53	0.30

Table 11: Comparison of the pick-up of 7-day weathered crude oil between duck and penguin feather clusters using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates.

	Duck feather		Penguin feather	
N	F (%)	SE	F (%)	SE
1	37.64	4.34	16.86	2.49
2	59.17	3.75	48.81	4.35
3	76.59	2.69	75.86	3.07
4	84.00	2.58	84.35	2.47
5	91.56	1.76	88.02	1.92
6	96.16	1.02	90.60	1.59
7	97.61	0.54	92.72	0.97
8	98.19	0.39	94.11	0.94
9	98.79	0.33	94.86	0.76
10	99.05	0.21	95.26	0.70
11	99.25	0.14	95.82	0.58
12	99.37	0.12	96.24	0.50
13	99.37	0.10	96.97	0.40
14	99.35	0.10	97.21	0.35

Table 12: Comparison of the pick-up of 14-day weathered crude oil between duck and penguin feather clusters using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22°C.

N	Duck feather		Penguin feather	
	F (%)	SE	F (%)	SE
1	15.276	2.94	10.80	0.79
2	37.930	5.40	42.57	5.52
3	58.953	6.25	66.10	6.19
4	75.505	7.53	79.62	4.10
5	85.056	5.50	86.32	2.62
6	92.299	3.21	90.12	2.18
7	96.060	2.10	91.47	1.95
8	97.456	1.46	92.67	1.86
9	98.773	0.37	93.44	1.65
10	99.151	0.17	94.45	1.59
11	99.263	0.12	95.20	1.29
12	99.309	0.09	96.05	0.92
13	99.335	0.07	96.70	0.59
14	99.349	0.489	96.99	0.46

Table 13: Comparison of bunker oil removal from duck feathers F (%) for different times of weathering using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22°C.

N	14 day weathering			7 day weathering			1 day weathering		
	F (%)	SE	95%	F (%)	SE	95%	F (%)	SE	95%
1	26.22	3.080	8.549	31.137	2.749	7.630	43.313	2.303	6.394
2	49.52	4.591	12.745	54.251	3.361	9.330	65.520	2.594	7.200
3	64.62	3.393	9.418	67.104	1.776	4.930	75.621	3.048	8.460
4	72.99	3.022	8.390	75.975	1.982	5.503	84.938	2.325	6.454
5	83.10	1.833	5.088	82.980	2.068	5.740	89.017	1.711	4.750
6	87.85	2.139	5.937	88.225	1.480	4.109	94.431	0.989	2.746
7	92.09	1.766	4.904	92.598	1.725	4.788	96.900	0.466	1.293
8	94.19	1.413	3.922	95.728	0.715	1.986	98.352	0.577	1.602
9	96.46	0.915	2.539	97.787	0.440	1.223	99.015	0.253	0.702
10	98.52	0.294	0.815	98.769	0.146	0.405	99.135	0.232	0.644
11	99.02	0.202	0.562	99.154	0.108	0.299			
12	99.33	0.167	0.463	99.352	0.070	0.194			

Table 14: The removal, F (%), of one-day weathered bunker oil from duck feathers using the optimal iron powder grade - MH300.29.Experiments were conducted in five replicates at ca. 22°C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	42.13	47.96	37.90	49.38	39.19	43.31	5.15	11.89	2.30	6.39
2	69.27	71.26	58.43	68.47	60.18	65.52	5.80	8.85	2.59	7.20
3	81.46	81.86	67.13	77.97	69.69	75.62	6.81	9.01	3.05	8.46
4	91.16	88.85	78.79	84.99	80.90	84.94	5.20	6.12	2.32	6.45
5	92.98	93.23	85.83	87.62	85.41	89.02	3.83	4.30	1.71	4.75
6	96.01	97.46	92.30	93.59	92.79	94.43	2.21	2.34	0.99	2.75
7	97.36	98.42	95.79	96.77	96.15	96.90	1.04	1.07	0.47	1.29
8	99.39	99.17	96.20	98.14	98.85	98.35	1.29	1.31	0.58	1.60
9	99.50	99.39	98.30	98.51	99.38	99.02	0.57	0.57	0.25	0.70
10	99.60	99.45	98.46	98.70	99.47	99.13	0.52	0.52	0.23	0.64

Table 15: The removal, F (%), of 7-day weathered bunker oil from duck feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22 °C.

N	Five replicates (F%)					F%(mean)	S	% CV	SE	95%
1	30.21	33.07	31.29	39.09	22.02	31.14	6.15	19.74	2.75	7.63
2	52.39	58.28	52.63	64.07	43.90	54.25	7.52	13.85	3.36	9.33
3	63.18	67.63	66.13	73.59	65.00	67.10	3.97	5.92	1.78	4.93
4	78.80	75.02	74.45	81.60	70.00	75.97	4.43	5.83	1.98	5.50
5	86.84	81.86	80.36	88.51	77.33	82.98	4.62	5.57	2.07	5.74
6	90.89	85.14	88.63	91.90	84.55	88.22	3.31	3.75	1.48	4.11
7	95.55	88.41	91.57	97.58	89.87	92.60	3.86	4.16	1.72	4.79
8	96.56	94.78	94.51	98.17	94.62	95.73	1.60	1.67	0.72	1.99
9	98.12	98.43	96.32	98.77	97.30	97.79	0.98	1.01	0.44	1.22
10	98.68	99.00	98.74	99.14	98.29	98.77	0.33	0.33	0.15	0.41
11	98.88	99.39	99.21	99.38	98.93	99.15	0.24	0.24	0.11	0.30
12	99.15	99.47	99.37	99.53	99.25	99.35	0.16	0.16	0.07	0.19

Table 16: The removal, F (%), of 14-day weathered bunker oil from duck feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22 ^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	21.91	21.80	21.62	28.32	37.44	26.22	6.89	26.26	3.08	8.55
2	37.52	45.82	44.07	57.73	62.44	49.52	10.27	20.73	4.59	12.74
3	52.52	64.87	64.47	68.17	73.06	64.62	7.59	11.74	3.39	9.42
4	62.10	74.77	72.22	75.56	80.32	72.99	6.76	9.26	3.02	8.39
5	82.43	82.18	78.77	82.22	89.91	83.10	4.10	4.93	1.83	5.09
6	85.27	88.05	83.16	87.03	95.73	87.85	4.78	5.44	2.14	5.94
7	90.22	93.13	88.49	90.12	98.49	92.09	3.95	4.29	1.77	4.90
8	94.87	94.16	90.48	92.47	98.96	94.19	3.16	3.35	1.41	3.92
9	96.94	97.27	93.73	95.27	99.11	96.46	2.05	2.12	0.91	2.54
10	97.71	98.97	98.03	98.59	99.31	98.52	0.66	0.67	0.29	0.81
11	98.36	99.23	98.75	99.29	99.46	99.02	0.45	0.46	0.20	0.56
12	98.71	99.45	99.29	99.67	99.52	99.33	0.37	0.38	0.17	0.46

Table 17: Comparison of bunker oil removal, F (%), from penguin feathers for different times of weathering using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca.22^{o}C.

	14-day weathering			7-day weathering			1-day weathering		
N	F%	SE	95%	F%	SE	95%	F%	SE	95%
1	37.43	3.318	9.211	53.070	3.735	10.368	64.901	2.236	6.207
2	66.20	2.753	7.641	79.976	1.591	4.416	88.516	0.711	1.974
3	81.80	1.441	4.001	87.472	0.542	1.505	94.413	0.508	1.411
4	87.71	1.059	2.941	90.943	0.462	1.281	96.267	0.338	0.940
5	90.39	0.600	1.665	92.516	0.363	1.007	96.927	0.381	1.057
6	92.66	0.429	1.191	93.616	0.304	0.843	97.474	0.373	1.035
7	94.11	0.419	1.162	94.458	0.275	0.764	97.806	0.365	1.014
8	95.31	0.250	0.693	95.394	0.280	0.778	98.150	0.365	1.013
9	96.16	0.229	0.637	96.386	0.173	0.480	98.399	0.370	1.027
10	96.81	0.145	0.402	96.944	0.131	0.365	98.553	0.364	1.011
11	97.23	0.097	0.268	97.329	0.091	0.253			
12	97.40	0.123	0.341	97.556	0.069	0.192			

Table 18: The removal, F (%), of one-day weathered bunker oil from penguin feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca.22 ^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	66.97	59.92	67.65	59.36	70.61	64.90	5.00	7.70	2.24	6.21

2	87.91	88.65	89.36	86.21	90.45	88.52	1.59	1.80	0.71	1.97
3	93.29	95.95	94.73	93.29	94.81	94.41	1.14	1.20	0.51	1.41
4	95.79	97.43	96.31	95.43	96.37	96.27	0.76	0.79	0.34	0.94
5	96.60	98.22	97.05	95.88	96.88	96.93	0.85	0.88	0.38	1.06
6	97.40	98.42	97.58	96.15	97.82	97.47	0.83	0.86	0.37	1.04
7	97.67	98.72	98.10	96.51	98.03	97.81	0.82	0.84	0.37	1.01
8	98.12	99.11	98.21	96.87	98.44	98.15	0.82	0.83	0.36	1.01
9	98.57	99.21	98.31	97.05	98.86	98.40	0.83	0.84	0.37	1.03
10	98.75	99.31	98.42	97.22	99.07	98.55	0.81	0.83	0.36	1.01

Table 19: The removal, F (%), of seven-day weathered bunker oil from penguin feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22 ^{o}C.

N	**Five replicates (F%)**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	52.03	62.59	52.85	40.19	57.69	53.07	8.35	15.74	3.74	10.37
2	77.11	84.66	78.08	77.11	82.91	79.98	3.56	4.45	1.59	4.42
3	85.54	88.60	87.11	87.87	88.24	87.47	1.21	1.39	0.54	1.51
4	89.38	90.88	92.27	91.14	91.06	90.94	1.03	1.13	0.46	1.28
5	91.13	93.16	92.82	92.51	92.96	92.52	0.81	0.88	0.36	1.01
6	92.55	94.20	94.11	93.35	93.87	93.62	0.68	0.73	0.30	0.84
7	93.65	95.13	94.75	93.99	94.77	94.46	0.62	0.65	0.28	0.76
8	94.41	96.06	95.76	95.25	95.48	95.39	0.63	0.66	0.28	0.78
9	95.73	96.58	96.41	96.73	96.48	96.39	0.39	0.40	0.17	0.48
10	96.60	97.10	96.87	97.36	96.78	96.94	0.29	0.30	0.13	0.36
11	97.15	97.41	97.42	97.57	97.09	97.33	0.20	0.21	0.09	0.25
12	97.59	97.62	97.61	97.68	97.29	97.56	0.15	0.16	0.07	0.19

Table 20: The removal, F (%), of 14-day weathered bunker oil from penguin feathers, using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22 ^{o}C.

N	**Five replicates (F%)**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	41.14	26.84	35.39	36.90	46.90	37.43	7.42	19.82	3.32	9.21
2	66.29	66.21	59.74	62.69	76.08	66.20	6.15	9.30	2.75	7.64
3	82.67	84.33	77.76	79.14	85.11	81.80	3.22	3.94	1.44	4.00
4	87.52	88.25	89.61	83.76	89.41	87.71	2.37	2.70	1.06	2.94
5	89.90	90.40	91.08	88.49	92.08	90.39	1.34	1.48	0.60	1.67
6	92.86	92.36	93.38	91.16	93.55	92.66	0.96	1.04	0.43	1.19
7	94.95	93.44	94.76	92.81	94.58	94.11	0.94	0.99	0.42	1.16
8	95.71	94.91	95.50	94.55	95.87	95.31	0.56	0.59	0.25	0.69
9	96.67	95.69	96.23	95.58	96.64	96.16	0.51	0.53	0.23	0.64
10	96.95	96.47	96.88	96.51	97.25	96.81	0.32	0.33	0.14	0.40
11	97.14	97.16	97.24	97.02	97.59	97.23	0.22	0.22	0.10	0.27
12	97.24	97.35	97.42	97.13	97.85	97.40	0.28	0.28	0.12	0.34

Table 21: Comparison of the pick-up of 1 day weathered bunker oil, F (%), between duck and penguin feather clusters using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates at ca. 22^0C.

N	Duck feather			Penguin feather		
	F%	**SE**	**95%**	**F%**	**SE**	**95%**
1	43.313	2.303	6.394	64.901	2.236	6.207
2	65.520	2.594	7.200	88.516	0.711	1.974
3	75.621	3.048	8.460	94.413	0.508	1.411
4	84.938	2.325	6.454	96.267	0.338	0.940
5	89.017	1.711	4.750	96.927	0.381	1.057
6	94.431	0.989	2.746	97.474	0.373	1.035
7	96.900	0.466	1.293	97.806	0.365	1.014
8	98.352	0.577	1.602	98.150	0.365	1.013
9	99.015	0.253	0.702	98.399	0.370	1.027
10	99.135	0.232	0.644	98.553	0.364	1.011

Table 22: Comparison of the pick-up of 7 day weathered bunker oil, F (%), between duck and penguin feather clusters using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates.

	Duck feather		Penguin feather	
N	**F%**	**SE**	**F%**	**SE**
1	31.14	2.749	53.07	3.735
2	54.25	3.361	79.98	1.591
3	67.10	1.776	87.47	0.542
4	75.97	1.982	90.94	0.462
5	82.98	2.068	92.52	0.363
6	88.22	1.480	93.62	0.304
7	92.60	1.725	94.46	0.275
8	95.73	0.715	95.39	0.280
9	97.79	0.440	96.39	0.173
10	98.77	0.146	96.94	0.131
11	99.15	0.108	97.33	0.091
12	99.35	0.070	97.56	0.069

Table 23: Comparison of the pick-up of 14-day weathered bunker oil F (%), between duck and penguin feather clusters using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates.

	Duck feather			Penguin feather		
N	F%	SE	95%	F%	SE	95%
1	26.22	3.080	8.549	37.43	3.318	9.211
2	49.52	4.591	12.745	66.20	2.753	7.641
3	64.62	3.393	9.418	81.80	1.441	4.001
4	72.99	3.022	8.390	87.71	1.059	2.941
5	83.10	1.833	5.088	90.39	0.600	1.665
6	87.85	2.139	5.937	92.66	0.429	1.191
7	92.09	1.766	4.904	94.11	0.419	1.162
8	94.19	1.413	3.922	95.31	0.250	0.693
9	96.46	0.915	2.539	96.16	0.229	0.637
10	98.52	0.294	0.815	96.81	0.145	0.402
11	99.02	0.202	0.562	97.23	0.097	0.268
12	99.33	0.167	0.463	97.40	0.123	0.341

Table 24: Comparison of the removal (F%) of the seven-day weathered oil from duck feathers between crude oil and bunker oil, using the optimal iron powder grade - MH300.29.

	Crude oil			**Bunker oil**		
N	**F%**	**95%**	**SE**	**F%**	**SE**	**95%**
1	37.64	12.05	4.34	31.14	2.75	7.63
2	59.17	10.41	3.75	54.25	3.36	9.33
3	76.59	7.47	2.69	67.10	1.78	4.93
4	84.00	7.16	2.58	75.97	1.98	5.50
5	91.56	4.87	1.76	82.98	2.07	5.74
6	96.16	2.83	1.02	88.22	1.48	4.11
7	97.61	1.50	0.54	92.60	1.72	4.79
8	98.19	1.07	0.39	95.73	0.72	1.99
9	98.79	0.93	0.33	97.79	0.44	1.22
10	99.05	0.58	0.21	98.77	0.15	0.41
11	99.25	0.38	0.14	99.15	0.11	0.30
12	99.37	0.35	0.12	99.35	0.07	0.19
13	99.37	0.28	0.10			
14	99.35	0.29	0.10			

Table 25: Comparison of removal (F%) of the one-day weathered oil from duck feathers between crude oil and bunker oil, using the optimal iron powder grade - MH300.29.

	Bunker oil	Crude oil

N	F%	SE	95%	F%	95%	SE
1	43.31	2.30	6.39	66.10	12.36	4.45
2	65.52	2.59	7.20	83.43	6.14	2.21
3	75.62	3.05	8.46	92.66	7.41	2.67
4	84.94	2.32	6.45	96.83	3.12	1.12
5	89.02	1.71	4.75	98.43	0.95	0.34
6	94.43	0.99	2.75	99.04	0.54	0.19
7	96.90	0.47	1.29	99.24	0.46	0.17
8	98.35	0.58	1.60	99.30	0.42	0.15
9	99.02	0.25	0.70	99.39	0.35	0.12
10	99.13	0.23	0.64	99.43	0.32	0.12

Table 26: Comparison of removal (F%) of the 14-day weathered oil from duck feathers between crude oil and bunker oil, using the optimal iron powder grade - MH300.29.

	Bunker oil		Crude oil	
	F%	SE	F%	SE
1	26.22	3.080	15.276	2.942
2	49.52	4.591	37.930	5.401
3	64.62	3.393	58.953	6.246
4	72.99	3.022	75.505	7.531
5	83.10	1.833	85.056	5.501
6	87.85	2.139	92.299	3.211
7	92.09	1.766	96.060	2.098
8	94.19	1.413	97.456	1.461
9	96.46	0.915	98.773	0.366
10	98.52	0.294	99.151	0.161
11	99.02	0.202	99.263	0.112
12	99.33	0.167	99.309	0.083
			99.335	0.061
			99.349	0.489

Table 27: Comparison of removal (F%) of the seven-day weathered oil from penguin feathers between crude oil and bunker oil.

	Crude oil			**Bunker oil**		
N	**F%**	**95%**	**SE**	**F%**	**SE**	**95%**
1	16.86	6.91	2.49	53.07	3.74	10.37
2	48.81	12.07	4.35	79.98	1.59	4.42
3	75.86	8.53	3.07	87.47	0.54	1.51
4	84.35	6.86	2.47	90.94	0.46	1.28
5	88.02	5.33	1.92	92.52	0.36	1.01
6	90.60	4.41	1.59	93.62	0.30	0.84
7	92.72	2.70	0.97	94.46	0.28	0.76
8	94.11	2.60	0.94	95.39	0.28	0.78

9	94.86	2.12	0.76	96.39	0.17	0.48
10	95.26	1.94	0.70	96.94	0.13	0.36
11	95.82	1.61	0.58	97.33	0.09	0.25
12	96.24	1.38	0.50	97.56	0.07	0.19

Table 28: Comparison of removal (F%) of the one-day weathered oil from penguin feathers between crude oil and bunker oil.

	Bunker oil			Crude oil		
N	F%	SE	95%	F%	95%	SE
1	64.90	2.24	6.21	56.41	5.52	1.99
2	88.52	0.71	1.97	75.29	8.42	3.03
3	94.41	0.51	1.41	83.80	8.24	2.97
4	96.27	0.34	0.94	89.50	4.84	1.74
5	96.93	0.38	1.06	93.00	4.34	1.56
6	97.47	0.37	1.04	94.65	3.12	1.12
7	97.81	0.37	1.01	95.66	2.27	0.82
8	98.15	0.36	1.01	96.21	1.94	0.70
9	98.40	0.37	1.03	96.61	1.51	0.55
10	98.55	0.36	1.01	96.85	1.43	0.51
11				97.07	1.22	0.47
12				97.32	0.92	0.39
13				97.47	0.91	0.38
14				97.53	0.83	0.31

Table 29: Comparison of removal (F%) of the 14-day weathered oil from penguin feathers between crude oil and bunker oil.

	Bunker oil			Crude oil		
N	F%	SE	95%	F%	95%	SE
1	37.43	2.43	6.74	10.80	2.18	0.79
2	66.20	2.75	7.64	42.57	14.99	5.52
3	81.80	1.44	4.00	66.10	17.19	6.19
4	87.71	1.06	2.94	79.62	11.38	4.10
5	90.39	0.60	1.67	86.32	7.27	2.62
6	92.66	0.43	1.19	90.12	6.05	2.18
7	94.11	0.42	1.16	91.47	5.42	1.95
8	95.31	0.25	0.69	92.67	5.18	1.86
9	96.16	0.23	0.64	93.44	4.57	1.65
10	96.81	0.14	0.40	94.45	4.42	1.59
11	97.23	0.10	0.27	95.20	3.59	1.29
12	97.40	0.12	0.34	96.05	2.54	0.92
13				96.70	1.64	0.62
14				96.99	1.29	0.48

Table 30: Removal of olive oil from a petri dish using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates.

Average R	Five replicates (P%)					P%(mean)	S	%CV	SE	95%
1.06	51.02	65.76	57.60	61.14	52.06	57.52	6.2	10.8	2.8	7.7
2.07	72.97	85.96	82.43	83.69	74.55	79.92	5.8	7.2	2.6	7.2
4.16	94.90	94.01	93.01	91.03	91.29	92.85	1.7	1.8	0.8	2.1
6.33	97.04	97.95	98.33	98.01	98.14	97.89	0.5	0.5	0.2	0.6
8.36	99.09	99.15	99.20	98.43	99.13	99.00	0.3	0.3	0.1	0.4
10.39	98.62	99.65	99.31	98.98	99.39	99.19	0.4	0.4	0.2	0.5
12.16	99.15	98.94	99.80	99.63	99.32	99.37	0.3	0.3	0.2	0.4

Table 31: Removal of olive oil from duck feathers using the optimal iron powder grade - MH300.29. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	94.58	97.53	96.40	97.13	97.42	96.61	1.22	1.26	0.54	1.51
2	99.19	99.60	99.24	99.59	99.24	99.37	0.20	0.21	0.09	0.25
3	99.80	99.79	99.80	99.64	99.52	99.71	0.13	0.13	0.06	0.16
4	99.93	99.87	99.90	99.74	99.64	99.82	0.12	0.12	0.06	0.15
5	99.99	99.90	99.92	99.82	99.71	99.87	0.11	0.11	0.05	0.13
6	99.99	99.92	99.93	99.84	99.76	99.89	0.09	0.09	0.04	0.11
7	99.94	99.76	99.95	99.87	99.80	99.86	0.08	0.08	0.04	0.10

Table 32: Different ways of applying olive oil as a pre-conditioner in the magnetic removal of seven-day weathered crude oil from penguin feathers. Experiments were conducted in three replicates.

Applying olive oil initially and between every 3 treatments		**Applying olive oil initially and between every 5 treatments**		**Not applying olive oil until N = 10 and then applying it once more time at N=15**		**Not applying olive oil until N =6 and then applying it once more time at N =10**	
No. of treatments	Oil removed (%)	No. of treatments	Oil removed (%)	No. of treatments	F (%)	No. of treatments	F (%)
3	36.10	5	50.89	1	14.88	1	16.43
6	50.00	10	70.45	2	44.31	2	46.34
9	63.31	15	87.02	3	72.76	3	69.93

12	75.35	20	96.79	4	83.64	4	84.89
15	88.44	25	99.00	5	86.81	5	91.92
18	93.43			6	88.92	**6**	**94.71**
21	97.43			7	90.84	7	96.86
22	98.02			8	92.96	8	97.61
23	98.59			9	93.44	9	98.28
				10	**94.83**	**10**	**97.61**
				11	95.36	11	98.47
				12	96.02	12	98.68
				13	96.37	13	98.91
				14	97.14	14	99.10
				15	**97.68**		
				16	98.16		
				17	98.56		
				18	98.95		
				19	99.07		
				20	99.10		

Table 33: Applying olive oil initially and between every 3 treatments

N	Three replicates (%)			F%(mean)	**S**	**%CV**	**SE**	**95%**
3	34.45	40.96	32.89	36.10	4.3	11.9	2.5	10.6
6	51.34	52.21	46.46	50.00	3.1	6.2	1.8	7.7
9	66.52	60.21	63.21	63.31	3.2	5.0	1.8	7.8
12	79.89	72.01	74.15	75.35	4.1	5.4	2.4	10.1
15	90.56	86.51	88.25	88.44	2.0	2.3	1.2	5.0
18	93.56	92.15	94.58	93.43	1.2	1.3	0.7	3.0
21	98.28	95.99	98.01	97.43	1.3	1.3	0.7	3.1
22	98.98	96.54	98.54	98.02	1.3	1.3	0.8	3.2
23	99.06	97.68	99.02	98.59	0.8	0.8	0.5	2.0

Table 34: Applying olive oil initially and between every 5 treatments (at N=1, N=6, N=11, N=16, N=21)

N	Three replicates (%)			F%(mean)	**S**	**%CV**	**SE**	**95%**
5	48.25	54.89	49.53	50.89	3.5	6.9	2.0	8.8
10	67.19	74.59	69.58	70.45	3.8	5.4	2.2	9.4
15	82.85	89.96	88.25	87.02	3.7	4.3	2.1	9.2
20	95.68	98.48	96.21	96.79	1.5	1.5	0.9	3.7
25	99.05	99.28	98.68	99.00	0.3	0.3	0.2	0.8

Table 35: Not applying olive oil until N=10 and then once more time at N=15

N	Three replicates (%)			F%(mean)	**S**	**%CV**	**SE**	**95%**
1	15.489	12.52	16.636	14.88	2.1	14.3	1.2	5.3
2	47.256	39.11	46.557	44.31	4.5	10.2	2.6	11.2
3	74.590	69.1	74.587	72.76	3.2	4.4	1.8	7.9
4	83.150	82.92	84.853	83.64	1.1	1.3	0.6	2.6
5	88.125	84.48	87.820	86.81	2.0	2.3	1.2	5.0
6	90.140	86.44	90.193	88.92	2.2	2.4	1.2	5.3
7	91.890	88.37	92.250	90.84	2.1	2.4	1.2	5.3
8	94.100	90.79	93.983	92.96	1.9	2.0	1.1	4.7
9	94.580	91.15	94.603	93.44	2.0	2.1	1.1	4.9
10	**95.240**	**94.08**	**95.180**	**94.83**	**0.7**	**0.7**	**0.4**	**1.6**
11	96.120	94.06	95.903	95.36	1.1	1.2	0.7	2.8
12	96.640	95.01	96.413	96.02	0.9	0.9	0.5	2.2
13	97.010	95.09	97.023	96.37	1.1	1.2	0.6	2.8
14	97.990	95.54	97.890	97.14	1.4	1.4	0.8	3.4
15	**98.440**	**96.19**	**98.400**	**97.68**	**1.3**	**1.3**	**0.7**	**3.2**
16	99.150	96.34	98.980	98.16	1.6	1.6	0.9	3.9
17	99.000	97.54	99.150	98.56	0.9	0.9	0.5	2.2
18	99.010	98.58	99.253	98.95	0.9	0.9	0.5	2.2
19	99.120	99.01	99.077	99.07	0.3	0.3	0.2	0.8
20	99.150	99.1	99.040	99.10	0.1	0.1	0.0	0.1

Table 36: Not applying olive oil until N=6 and once more time at N=10

No. of treatments	F1	F2	F3	F%(mean)	S	%CV	SE	95%
1	10.27	24.33	14.68	16.43	7.2	43.8	4.2	17.9
2	48.06	47.47	43.48	46.34	2.5	5.4	1.4	6.2
3	70.17	68.62	71.01	69.93	1.2	1.7	0.7	3.0
4	80.58	92.1	81.98	84.89	6.3	7.4	3.6	15.6
5	90.52	94.95	90.29	91.92	2.6	2.9	1.5	6.5
6	**93.57**	**95.88**	**94.68**	**94.71**	**1.2**	**1.2**	**0.7**	**2.9**
7	96.49	97.14	96.94	96.86	0.3	0.3	0.2	0.8
8	97.43	97.87	97.54	97.61	0.2	0.2	0.1	0.6
9	98.36	98.47	98.01	98.28	0.2	0.2	0.1	0.6
10	**97.08**	**97.94**	**97.81**	**97.61**	**0.5**	**0.5**	**0.3**	**1.2**
11	98.48	98.47	98.47	98.47	0.0	0.0	0.0	0.0
12	98.71	98.74	98.6	98.68	0.1	0.1	0.0	0.2
13	99.06	98.87	98.8	98.91	0.1	0.1	0.1	0.3
14	99.12	99.01	99.1	99.08	0.1	0.1	0.0	0.1

Table 37: Experimental data and statistical analysis for the pick-up of 7-day weathered crude oil from duck feather clusters using the optimal iron powder grade - MH300.29 and olive oil as a pre-conditioner. Experiments were conducted in five replicates. Olive oil is applied at N= 6 only.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	30.26	35.26	30.86	49.11	46.23	38.34	8.79	22.92	3.93	10.91
2	52.43	59.91	49.17	64.06	71.51	59.41	8.97	15.10	4.01	11.13
3	72.71	71.62	77.07	86.47	91.23	79.82	8.66	10.84	3.87	10.75
4	81.66	84.65	80.49	92.83	97.33	87.39	7.35	8.42	3.29	9.13
5	89.12	93.05	95.76	94.48	98.34	94.15	3.42	3.63	1.53	4.24
6	**98.15**	**97.51**	**94.52**	**96.20**	**96.97**	**96.67**	**1.40**	**1.45**	**0.62**	**1.73**
7	99.59	99.12	97.91	99.48	99.64	99.15	0.72	0.73	0.32	0.89
8	99.87	99.39	99.90	99.65	99.73	99.71	0.20	0.20	0.09	0.25
9	99.95	99.88	100.15	99.92	99.89	99.96	0.11	0.11	0.05	0.14
10	99.97	99.92	100.13	99.97	99.97	99.99	0.08	0.08	0.04	0.10

Table 38: Experimental data and statistical analysis for the pick-up of 7 day weathered crude oil from penguin feather clusters using the optimal iron powder grade - MH300.29 and olive oil as a pre-conditioner. Experiments were conducted in five replicates. Olive oil is applied at N= 6 and N=10

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	17.46	24.33	26.98	10.27	14.68	18.74	6.87	36.66	3.07	8.53
2	40.86	47.47	65.13	48.06	43.48	49.00	9.49	19.37	4.24	11.78
3	74.03	68.62	82.47	70.17	71.01	73.26	5.51	7.53	2.47	6.85
4	86.96	92.10	90.63	80.58	81.98	86.45	5.10	5.90	2.28	6.33
5	92.40	94.95	93.63	90.52	90.29	92.36	2.00	2.16	0.89	5.48
6	**95.26**	**95.88**	**95.97**	**93.57**	**94.68**	**95.07**	**0.99**	**1.04**	**0.44**	**1.23**
7	97.04	97.14	97.00	96.49	96.94	96.92	0.25	0.26	0.11	0.31
8	97.83	97.87	98.22	97.43	97.54	97.78	0.31	0.32	0.14	0.39
9	98.72	98.47	98.88	98.36	98.01	98.49	0.34	0.34	0.15	0.42
10	**97.73**	**97.94**	**98.22**	**97.08**	**97.81**	**97.75**	**0.42**	**0.43**	**0.19**	**0.52**
11	98.91	98.47	98.69	98.48	98.47	98.60	0.20	0.20	0.09	0.24
12	99.31	98.74	98.97	98.71	98.60	98.87	0.28	0.28	0.13	0.35
13	99.21	98.87	99.25	99.06	98.80	99.04	0.20	0.20	0.09	0.25

14	99.28	98.69	99.34	99.12	98.90	99.07	0.27	0.27	0.12	0.34

Table 39: Experimental data and statistical analysis for the pick-up of 14 day weathered bunker oil from duck feathers using the optimal iron powder grade - MH300.29, and olive oil as a pre-conditioner. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	26.93	30.20	33.05	21.34	21.58	26.62	5.18	19.47	2.32	6.44
2	55.26	60.16	56.84	38.27	48.09	51.73	8.72	16.86	3.90	10.83
3	69.07	73.92	72.84	66.05	63.11	69.00	4.54	6.57	2.03	5.63
4	77.39	79.70	79.94	74.21	74.68	77.18	2.70	3.49	1.21	3.35
5	85.51	83.13	88.95	85.49	84.73	85.56	2.13	2.49	0.95	2.64
6	97.05	95.49	94.52	94.67	92.75	94.89	1.56	1.65	0.70	1.94
7	98.92	97.13	98.03	97.76	98.52	98.07	0.69	0.70	0.31	0.85
8	99.36	98.57	99.16	98.94	99.17	99.04	0.30	0.31	0.14	0.38
9	99.62	99.33	99.50	99.30	99.46	99.44	0.13	0.13	0.06	0.16
10	99.74	99.50	99.67	99.51	99.65	99.61	0.10	0.11	0.05	0.13

Table 40: Experimental data and statistical analysis for the pick-up of 14 day weathered bunker oil from penguin feathers using the optimal iron powder grade - MH300.29, and olive oil as a pre-conditioner. Experiments were conducted in five replicates.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	37.72	31.97	44.20	33.75	36.70	36.87	4.70	12.74	2.10	5.83
2	67.19	74.46	67.88	63.80	74.68	69.60	4.79	6.88	2.14	5.95
3	76.13	78.18	86.13	87.70	85.83	82.79	5.25	6.34	2.35	6.51
4	87.86	86.26	90.78	90.28	90.22	89.08	1.94	2.18	0.87	2.41
5	91.10	88.51	92.64	92.18	91.68	91.22	1.62	1.78	0.72	2.01
6	95.83	94.26	97.86	96.90	95.61	96.09	1.36	1.42	0.61	1.69
7	97.31	96.41	98.42	98.54	97.26	97.59	0.89	0.91	0.40	1.10
8	98.52	97.23	98.70	99.14	98.17	98.35	0.72	0.73	0.32	0.89
9	99.07	97.74	99.26	99.31	98.81	98.84	0.64	0.65	0.29	0.80
10	99.26	98.26	99.44	99.40	99.18	99.11	0.49	0.49	0.22	0.60

Table 41: Comparison of the pick-up, F (%), of 7 day weathered crude oil from duck feather clusters with using olive oil and without using olive oil as a pre-conditioner. Experiments were conducted in five replicates.

	With olive oil		Without olive oil	
N	F (%)	SE	F (%)	SE

1	38.34	3.93	37.64	4.34
2	59.41	4.01	59.17	3.75
3	79.82	3.87	76.59	2.69
4	87.39	3.29	84.00	2.58
5	94.15	1.53	91.56	1.76
6	**96.67**	**0.62**	**96.16**	1.02
7	99.15	0.32	97.61	0.54
8	99.71	0.09	98.19	0.39
9	99.96	0.05	98.79	0.33
10	99.99	0.04	99.05	0.21
11			99.25	0.14
12			99.37	0.12
13			99.37	0.10
14			99.35	0.10

Table 42: Comparison of the pick-up, F (%), of 7 day weathered crude oil from penguin feather clusters with using olive oil and without using olive oil as a pre-conditioner. Experiments were conducted in five replicates.

	Without olive oil		**With olive oil**	
N	**F (%)**	SE	**F (%)**	**SE**
1	16.86	2.49	18.74	3.07
2	48.81	4.35	49.00	4.24
3	75.86	3.07	73.26	2.47
4	84.35	2.47	86.45	2.28
5	88.02	1.92	92.36	0.89
6	**90.60**	1.59	**95.07**	**0.44**
7	92.72	0.97	96.92	0.11
8	94.11	0.94	97.78	0.14
9	94.86	0.76	98.49	0.15
10	95.26	0.70	97.75	**0.19**
11	95.82	0.58	98.60	0.09
12	96.24	0.50	98.87	0.13
13	96.97	0.40	99.04	0.09
14	97.21	0.35	99.07	0.12

Table 43: Comparison of the pick-up, F (%), of 14 day weathered bunker oil from duck feather clusters with using olive oil and without using olive oil as a pre-conditioner. Experiments were conducted in five replicates

	Without olive oil			**With olive oil**		
N	F%	SE	95%	F%	SE	95%
1	26.219	3.080	8.549	26.621	2.318	6.435

2	49.516	4.591	12.745	51.726	3.900	10.825
3	64.617	3.393	9.418	68.998	2.029	5.632
4	72.994	3.022	8.390	77.184	1.206	3.347
5	83.102	1.833	5.088	85.563	0.952	2.642
6	87.849	2.139	5.937	94.895	0.699	1.942
7	92.090	1.766	4.904	98.072	0.308	0.854
8	94.189	1.413	3.922	99.040	0.136	0.378
9	96.463	0.915	2.539	99.441	0.058	0.161
10	98.525	0.294	0.815	99.613	0.047	0.130
11	99.017	0.202	0.562			
12	99.326	0.167	0.463			

Table 44: Comparison of the pick-up, F (%), of 14 day weathered bunker oil from penguin feather clusters with using olive oil and without using olive oil as a pre-conditioner. Experiments were conducted in five replicates.

	With olive oil			**Without olive oil**		
N	**F (%)**	**SE**	**95%**	**F (%)**	**SE**	**95%**
1	36.870	2.101	5.831	37.433	2.427	6.737
2	69.602	2.143	5.949	66.201	2.753	7.641
3	82.795	2.346	6.514	81.800	1.441	4.001
4	89.080	0.869	2.413	87.712	1.059	2.941
5	91.223	0.724	2.011	90.393	0.600	1.665
6	96.092	0.610	1.694	92.661	0.429	1.191
7	97.587	0.398	1.104	94.107	0.419	1.162
8	98.351	0.321	0.890	95.308	0.250	0.693
9	98.839	0.287	0.798	96.163	0.229	0.637
10	99.106	0.218	0.604	96.811	0.145	0.402
11				97.231	0.097	0.268
12				97.397	0.123	0.341

Table 45: Removal of weathered crude oil from plumage, using the optimal iron powder grade - MH300.29. Experiments were conducted in 5 patches at ca. 22 ^{o}C.

N	Five replicates (C%)					C(%)	S	%CV	SE	95%
1	22.68	26.32	23.17	34.13	32.89	27.836	5.382	19.336	2.407	6.682
2	40.41	43.08	46.02	50.17	48.96	45.728	4.046	8.848	1.809	5.023
3	58.38	54.97	50.36	62.93	57.22	56.770	4.609	8.118	2.061	5.722
4	62.69	67.64	60.87	71.77	66.67	65.928	4.291	6.508	1.919	5.327
5	69.78	70.57	69.20	74.83	76.10	72.095	3.148	4.366	1.408	3.908
6	76.49	75.89	75.56	79.84	79.96	77.548	2.173	2.802	0.972	2.698
7	80.05	81.56	81.69	86.58	85.04	82.983	2.714	3.270	1.214	3.369
8	83.88	86.15	84.34	89.74	89.71	86.764	2.833	3.265	1.267	3.517
9	89.07	88.35	87.39	92.37	90.05	89.445	1.903	2.128	0.851	2.363

10	92.35	89.95	90.14	93.95	91.39	91.554	1.656	1.809	0.741	2.056
11	93.81	92.38	91.28	94.53	93.72	93.145	1.296	1.392	0.580	1.609
12	94.81	94.38	93.28	95.23	94.72	94.485	0.735	0.778	0.329	0.913

Table 46: The removal of weathered crude oil from a whole penguin using the optimal iron powder grade - MH300.29, and olive oil as a pre-conditioner. Olive oil is applied only once at N = 6. Experiments were done in 5 replicates (in patches) at ca.22.C

N	Five replicates (in patches)					C(%)	S	%CV	SE	95%
1	22.68	27.32	23.17	24.13	32.89	26.036	4.235	16.266	1.894	5.258
2	40.51	43.02	44.09	55.17	42.90	45.138	5.758	12.757	2.575	7.149
3	58.38	59.97	50.36	62.93	57.22	57.770	4.663	8.071	2.085	5.789
4	62.61	67.69	65.84	71.77	66.60	66.902	3.313	4.953	1.482	4.113
5	73.78	70.57	74.20	74.83	76.10	73.895	2.058	2.785	0.920	2.555
6	74.00	77.27	78.24	80.07	72.78	76.472	3.019	3.948	1.350	3.748
7	85.20	85.64	87.74	82.13	82.84	84.708	2.261	2.669	1.011	2.806
8	86.97	88.91	90.23	90.83	84.91	88.367	2.437	2.758	1.090	3.026
9	92.87	92.55	92.61	91.89	88.98	91.778	1.607	1.751	0.719	1.995
10	94.50	93.27	93.47	94.53	91.75	93.507	1.138	1.217	0.509	1.413
11	95.56	96.36	95.34	95.59	92.67	95.105	1.413	1.486	0.632	1.754
12	96.98	96.91	96.55	97.10	95.12	96.532	0.816	0.845	0.365	1.013

Table 47: Comparison of the pick-up of 1-day weathered crude oil from plumage, C (%), with using olive oil and without using olive oil as a pre-conditioner. Experiments were done in 5 replicates at ca. 22^{o}C.

	Without olive oil		**With olive oil**	
N	C (%)	SE	C (%)	SE
1	27.836	2.407	26.036	1.894
2	45.728	1.809	45.138	2.575
3	56.770	2.061	57.770	2.085
4	65.928	1.919	66.902	1.482
5	72.095	1.408	73.895	0.920
6	77.548	0.972	76.472	1.350
7	82.983	1.214	84.708	1.011
8	86.764	1.267	88.367	1.090
9	89.445	0.851	91.778	0.719
10	91.554	0.741	93.507	0.509
11	93.145	0.580	95.105	0.632
12	94.485	0.329	96.532	0.365

Table 48: Comparison of the pick-up of weathered crude oil between feather clusters and plumage. Experiments were done in 5 replicates at ca. 22^{o}C.

	Feather cluster			Plumage		
N	**Oil removal**	**95%**	**SE**	**Oil removal**	**95%**	**SE**
1	56.412	5.518	1.988	27.836	6.682	2.407
2	75.293	8.416	3.032	45.728	5.023	1.809
3	83.801	8.240	2.968	56.770	5.722	2.061
4	89.499	4.836	1.742	65.928	5.327	1.919
5	93.004	4.337	1.562	72.095	3.908	1.408
6	94.650	3.120	1.124	77.548	2.698	0.972
7	95.663	2.269	0.817	82.983	3.369	1.214
8	96.205	1.940	0.699	86.764	3.517	1.267
9	96.614	1.514	0.545	89.445	2.363	0.851
10	96.855	1.426	0.514	91.554	2.056	0.741
11	97.072	1.221	0.440	93.145	1.609	0.580
12	97.320	0.925	0.333	94.485	0.913	0.329
13	97.473	0.907	0.327			
14	97.535	0.830	0.299			

Appendix 7

Abbreviation:

S: Standard deviation
% CV: co-efficient of variance
SE: Standard error
95%: 95% interval confidence

Shell crude oil (SO)

Table 1: Comparison between without and with using pre-conditioners in the magnetic removal, F (%), of weathered crude oil from duck feathers as a function of the number of treatments, N. Experiments were conducted in five replicates at ca. 22^{o}C

	No pre-conditioner			Olive oil			Blended oil (Canola/soybean)		
N	F(%)	95%	SE	F(%)	95%	SE	F(%)	SE	95%
1	37.641	12.047	4.340	38.344	10.910	3.930	35.257	3.095	8.591
2	59.168	10.408	3.749	59.413	11.135	4.011	69.411	2.632	7.306
3	76.595	7.466	2.689	79.818	10.746	3.871	84.115	1.662	4.614
4	83.997	7.161	2.579	87.394	9.130	3.289	90.579	0.917	2.547
5	91.558	4.874	1.756	94.148	4.245	1.529	96.539	0.726	2.016
6	**96.157**	**2.826**	**1.018**	**96.670**	**1.735**	**0.625**	**98.547**	**0.285**	**0.792**
7	97.613	1.500	0.540	99.147	0.893	0.322	99.243	0.121	0.335
8	98.193	1.073	0.386	99.707	0.252	0.091	99.388	0.127	0.353
79	98.788	0.925	0.333	99.957	0.137	0.049	99.461	0.119	0.331
10	99.046	0.585	0.211	99.992	0.099	0.036			
11	99.249	0.305	0.110						
12	99.370	0.278	0.100						
13	99.375	0.228	0.082						
14	99.354	0.234	0.084						

Table 1 (cont.): Comparison between without and with using pre-conditioners in the magnetic removal, F (%), of weathered crude oil from duck feathers as a function of the number of treatments, N. Experiments were conducted in five replicates at ca. 22^{o}C.

Canola oil			De-oiler (BD1)			Bio-dispersol			Methyl oleate		
(F(%)	SE	95%	(F(%)	SE	95%	(F(%)	SE	95%	(F(%)	SE	95%
38.836	2.330	6.467	37.410	2.831	7.860	39.424	2.254	6.258	36.029	2.611	7.249
69.685	3.094	8.588	73.739	2.829	7.854	66.357	3.264	9.061	64.383	2.732	7.584
85.707	1.784	4.953	86.750	2.311	6.416	81.149	2.476	6.874	78.059	2.539	7.049
93.994	1.145	3.178	94.111	0.957	2.656	92.374	1.364	3.788	88.096	1.406	3.902
97.279	0.527	1.463	97.617	0.437	1.214	96.120	0.622	1.725	95.356	0.598	1.660
98.462	**0.383**	**1.064**	**99.266**	**0.192**	**0.532**	**98.301**	**0.353**	**0.980**	**98.853**	**0.304**	**0.845**
99.356	0.150	0.416	99.667	0.089	0.248	99.373	0.067	0.186	99.474	0.088	0.245
99.613	0.099	0.275	99.819	0.074	0.205	99.718	0.071	0.197	99.722	0.043	0.120
99.680	0.082	0.227	99.870	0.079	0.219	99.778	0.072	0.199	99.776	0.047	0.131

Table 2: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather without using any pre-conditioner (using iron powder only). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	51.68	24.87	34.20	37.63	39.82	37.64	9.70	25.78	4.34	12.05
2	69.44	48.55	65.62	54.98	57.26	59.17	8.38	14.17	3.75	10.41
3	80.39	73.76	83.25	67.84	77.73	76.59	6.01	7.85	2.69	7.47
4	89.96	84.66	85.94	74.40	85.03	84.00	5.77	6.87	2.58	7.16
5	92.76	93.58	93.09	84.57	93.79	91.56	3.93	4.29	1.76	4.87
6	98.41	96.11	97.54	92.45	96.27	96.16	2.28	2.37	1.02	2.83
7	98.91	97.83	98.15	95.67	97.50	97.61	1.21	1.24	0.54	1.50
8	99.02	98.22	98.77	96.79	98.18	98.19	0.86	0.88	0.39	1.07
9	99.34	99.10	99.24	97.52	98.74	98.79	0.75	0.75	0.33	0.93
10	99.39	99.19	99.40	98.26	98.99	99.05	0.47	0.48	0.21	0.58
11	99.51	99.28	99.46	98.74	99.25	99.25	0.30	0.31	0.14	0.38
12	99.55	99.49	99.55	98.89	99.37	99.37	0.28	0.28	0.12	0.35
13	99.52	99.48	99.56	99.00	99.32	99.37	0.23	0.23	0.10	0.28
14	99.57	99.44	99.50	98.98	99.28	99.35	0.23	0.24	0.10	0.29

Table 3: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather using olive oil as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	30.26	35.26	30.86	49.11	46.23	38.34	8.79	22.92	3.93	10.91
2	52.43	59.91	49.17	64.06	71.51	59.41	8.97	15.10	4.01	11.13
3	72.71	71.62	77.07	86.47	91.23	79.82	8.66	10.84	3.87	10.75
4	81.66	84.65	80.49	92.83	97.33	87.39	7.35	8.42	3.29	9.13
5	89.12	93.05	95.76	94.48	98.34	94.15	3.42	3.63	1.53	4.24
6	98.15	97.51	94.52	96.20	96.97	96.67	1.40	1.45	0.62	1.73
7	99.59	99.12	97.91	99.48	99.64	99.15	0.72	0.73	0.32	0.89
8	99.87	99.39	99.90	99.65	99.73	99.71	0.20	0.20	0.09	0.25
9	99.95	99.88	100.15	99.92	99.89	99.96	0.11	0.11	0.05	0.14
10	99.97	99.92	100.13	99.97	99.97	99.99	0.08	0.08	0.04	0.10

Table 4: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather using methyl oleate as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	36.05	35.15	45.77	32.35	30.82	36.03	5.84	16.21	2.61	7.25
2	58.51	66.74	73.67	63.29	59.71	64.38	6.11	9.49	2.73	7.58
3	75.63	78.09	87.84	74.46	74.26	78.06	5.68	7.27	2.54	7.05
4	85.95	89.37	92.84	84.88	87.44	88.10	3.14	3.57	1.41	3.90
5	95.59	94.71	96.90	93.44	96.14	95.36	1.34	1.40	0.60	1.66
6	99.52	98.82	97.76	98.86	99.31	98.85	0.68	0.69	0.30	0.85
7	99.64	99.15	99.55	99.44	99.59	99.47	0.20	0.20	0.09	0.24
8	99.78	99.71	99.65	99.62	99.86	99.72	0.10	0.10	0.04	0.12
9	99.88	99.75	99.71	99.65	99.89	99.78	0.11	0.11	0.05	0.13

Table 5: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather using bio-dispersol as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	37.89	46.72	38.90	32.80	40.81	39.42	5.04	12.79	2.25	6.26
2	69.09	63.98	55.78	75.71	67.23	66.36	7.30	11.00	3.26	9.06
3	83.92	82.92	71.28	84.18	83.44	81.15	5.54	6.82	2.48	6.87
4	94.74	91.04	88.05	95.71	92.33	92.37	3.05	3.30	1.36	3.79
5	96.12	95.43	94.23	97.83	97.00	96.12	1.39	1.45	0.62	1.73
6	98.41	98.97	96.94	98.61	98.58	98.30	0.79	0.80	0.35	0.98
7	99.41	99.43	99.25	99.20	99.58	99.37	0.15	0.15	0.07	0.19
8	99.93	99.74	99.79	99.59	99.54	99.72	0.16	0.16	0.07	0.20
9	99.97	99.82	99.87	99.61	99.62	99.78	0.16	0.16	0.07	0.20

Table 6: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather using de-oiler (BD1) as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	33.48	35.24	47.97	32.12	38.24	37.41	6.33	16.92	2.83	7.86
2	66.61	67.24	76.83	79.97	78.05	73.74	6.33	8.58	2.83	7.85
3	82.73	80.20	91.27	91.90	87.66	86.75	5.17	5.96	2.31	6.42
4	91.61	92.17	96.43	95.75	94.59	94.11	2.14	2.27	0.96	2.66
5	97.17	97.21	98.82	98.43	96.46	97.62	0.98	1.00	0.44	1.21
6	99.28	99.67	99.48	99.36	98.54	99.27	0.43	0.43	0.19	0.53
7	99.43	99.85	99.79	99.79	99.47	99.67	0.20	0.20	0.09	0.25
8	99.54	99.94	99.89	99.93	99.79	99.82	0.17	0.17	0.07	0.21
9	99.56	99.96	99.93	99.94	99.97	99.87	0.18	0.18	0.08	0.22

Table 7: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather using Canola oil as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	S	%CV	SE	95%
1	33.20	34.25	39.25	45.67	41.82	38.84	5.21	13.41	2.33	6.47
2	61.34	62.95	75.16	74.80	74.18	69.68	6.92	9.93	3.09	8.59
3	86.20	79.58	89.14	89.23	84.39	85.71	3.99	4.65	1.78	4.95
4	93.36	90.36	97.11	95.63	93.52	93.99	2.56	2.72	1.14	3.18
5	97.68	95.43	98.69	97.37	97.22	97.28	1.18	1.21	0.53	1.46
6	98.28	97.04	98.86	99.05	99.08	98.46	0.86	0.87	0.38	1.06
7	99.33	98.83	99.50	99.38	99.74	99.36	0.33	0.34	0.15	0.42
8	99.45	99.36	99.57	99.85	99.84	99.61	0.22	0.22	0.10	0.28
9	99.54	99.50	99.61	99.89	99.86	99.68	0.18	0.18	0.08	0.23

Table 8: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered crude oil from duck feather using blended oil (Canola/soybean) as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates (F%)					F%(mean)	s	%CV	SE	95%
1	33.59	34.53	45.05	37.26	25.86	35.26	6.92	19.63	3.09	8.59
2	74.62	70.09	74.27	60.20	67.86	69.41	5.89	8.48	2.63	7.31
3	87.44	84.97	87.71	79.87	80.58	84.11	3.72	4.42	1.66	4.61
4	91.86	89.34	92.90	87.74	91.06	90.58	2.05	2.26	0.92	2.55
5	96.49	96.51	97.21	94.01	98.47	96.54	1.62	1.68	0.73	2.02
6	99.01	99.14	98.35	97.55	98.69	98.55	0.64	0.65	0.29	0.79
7	99.41	99.61	98.97	99.22	99.01	99.24	0.27	0.27	0.12	0.33
8	99.57	99.78	99.06	99.25	99.28	99.39	0.28	0.29	0.13	0.35
9	99.60	99.83	99.13	99.35	99.39	99.46	0.27	0.27	0.12	0.33

Table 9: The relative values for N_{99} for the six pre-conditioners tested compared to that in the absence of a pre-conditioner in the magnetic removal of weathered crude oil from duck feathers.

	No pre-conditioner	Olive oil	Blended oil	Bio-dispersol	Canola oil	Methyl oleate	De-oiler (BD1)
Replicate 1	7.80	6.40	5.90	6.00	5.90	5.80	5.10
Replicate 2	8.40	6.70	6.00	6.30	6.00	5.80	5.50
Replicate 3	8.80	6.80	6.80	6.50	6.20	6.10	5.60
Replicate 4	10.10	6.80	7.00	6.60	6.60	6.10	5.80
Replicate 5	13.00	7.40	7.10	6.90	7.20	6.60	6.40
Mean	**9.62**	**6.82**	**6.56**	**6.46**	**6.38**	**6.08**	**5.68**
s	2.07	0.36	0.57	0.34	0.53	0.33	0.48
SE	0.93	0.16	0.25	0.15	0.24	0.15	0.21

Table 10: Relative values of k_C for the six pre-conditioners tested compared to the k_C value in the absence of a pre-conditioner.

	Crude oil	
	k_C	SE
No pre-conditioner	0.635	0.020
Olive oil	1.270	0.070
Blended oil	1.262	0.060
Canola oil	1.451	0.050
Bio-dispersol	1.606	0.070
De-oiler (BD1)	1.236	0.050
Methyl oleate	1.679	0.100

Bunker oil (BO2)

Table 11: Comparison between without and with using pre-conditioners in the removal, F (%), of weathered bunker oil from duck feathers as a function of the number of treatments, N. Experiments were conducted in five replicates at ca. 22°C.

	No pre-conditioner			**Olive oil**			**De-oiler (BD1)**		
N	F (%)	SE	95%	F (%)	SE	95%	F (%)	SE	95%
1	26.22	3.08	8.55	26.62	2.32	6.44	28.74	3.01	8.34
2	49.52	4.59	12.74	51.73	3.90	10.83	58.62	1.47	4.07
3	64.62	3.39	9.42	69.00	2.03	5.63	74.09	0.92	2.55
4	72.99	1.59	4.41	77.18	1.21	3.35	81.17	1.52	4.22
5	83.10	1.83	5.09	85.56	0.95	2.64	88.88	0.83	2.29
6	**87.85**	**2.14**	**5.94**	**94.89**	**0.70**	**1.94**	**98.51**	**0.21**	**0.57**
7	92.09	1.77	4.90	98.07	0.31	0.85	99.31	0.10	0.27
8	94.19	1.41	3.92	99.04	0.14	0.38	99.64	0.06	0.17
9	96.46	0.91	2.54	99.44	0.06	0.16	99.78	0.04	0.11
10	98.52	0.29	0.81	99.61	0.05	0.13	99.81	0.03	0.10
11	99.02	0.20	0.56						
12	99.33	0.17	0.46						

Table 11 (cont.): Comparison between without and with using pre-conditioners in the removal, F (%), of weathered bunker oil from duck feathers as a function of the number of treatments, N. Experiments were conducted in five replicates at ca. 22^{o}C.

Canola			**Blended oil**			**Methyl oleate**			**Bio-dispersol**		
F (%)	SE	95%	F (%)	SE	95%	F (%)	SE	95%	F (%)	SE	95%
26.51	2.23	6.18	26.67	2.76	7.66	27.92	2.72	7.54	27.17	2.63	7.29
58.93	2.58	7.17	56.06	2.55	7.07	58.75	3.12	8.65	62.38	2.69	7.46
73.71	0.65	1.82	71.65	1.95	5.40	77.56	2.46	6.82	75.58	2.47	6.85
81.28	0.76	2.12	80.92	1.54	4.27	85.20	1.77	4.91	86.37	1.82	5.04
88.51	1.26	3.51	89.65	1.13	3.15	89.56	1.22	3.37	90.04	1.37	3.81
97.60	**0.34**	**0.94**	**96.40**	**0.68**	**1.90**	**98.71**	**0.23**	**0.64**	**97.57**	**0.48**	**1.34**
98.88	0.17	0.47	98.21	0.44	1.23	99.47	0.08	0.21	99.29	0.05	0.15
99.33	0.11	0.31	98.75	0.43	1.20	99.83	0.03	0.07	99.59	0.09	0.24
99.54	0.11	0.30	99.06	0.33	0.93	99.86	0.02	0.06	99.74	0.04	0.12
99.63	0.08	0.22	99.26	0.27	0.75	99.90	0.03	0.07	99.87	0.02	0.06

Table 12: Experimental data and statistical analysis of the removal, F (%), of weathered bunker oil from duck feather without using pre-conditioner. Experiments were conducted in five replicates at ca. 22^{o}C.

N	**Five replicates**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	21.91	21.80	21.62	28.32	37.44	26.22	6.89	26.26	3.08	8.55
2	37.52	45.82	44.07	57.73	62.44	49.52	10.27	20.73	4.59	12.74
3	52.52	64.87	64.47	68.17	73.06	64.62	7.59	11.74	3.39	9.42
4	67.10	74.77	72.22	75.56	75.32	72.99	3.55	4.87	1.59	4.41
5	82.43	82.18	78.77	82.22	89.91	83.10	4.10	4.93	1.83	5.09
6	85.27	88.05	83.16	87.03	95.73	87.85	4.78	5.44	2.14	5.94
7	90.22	93.13	88.49	90.12	98.49	92.09	3.95	4.29	1.77	4.90
8	94.87	94.16	90.48	92.47	98.96	94.19	3.16	3.35	1.41	3.92
9	96.94	97.27	93.73	95.27	99.11	96.46	2.05	2.12	0.91	2.54
10	97.71	98.97	98.03	98.59	99.31	98.52	0.66	0.67	0.29	0.81
11	98.36	99.23	98.75	99.29	99.46	99.02	0.45	0.46	0.20	0.56
12	98.71	99.45	99.29	99.67	99.52	99.33	0.37	0.38	0.17	0.46

Table 13: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered bunker oil from duck feather using olive oil as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	**Five replicates**					**F%(mean)**	**S**	**%CV**	**SE**	**95%**
1	26.93	30.20	33.05	21.34	21.58	26.62	5.18	19.47	2.32	6.44
2	55.26	60.16	56.84	38.27	48.09	51.73	8.72	16.86	3.90	10.83
3	69.07	73.92	72.84	66.05	63.11	69.00	4.54	6.57	2.03	5.63
4	77.39	79.70	79.94	74.21	74.68	77.18	2.70	3.49	1.21	3.35
5	85.51	83.13	88.95	85.49	84.73	85.56	2.13	2.49	0.95	2.64
6	97.05	95.49	94.52	94.67	92.75	94.89	1.56	1.65	0.70	1.94
7	98.92	97.13	98.03	97.76	98.52	98.07	0.69	0.70	0.31	0.85

8	99.36	98.57	99.16	98.94	99.17	99.04	0.30	0.31	0.14	0.38
9	99.62	99.33	99.50	99.30	99.46	99.44	0.13	0.13	0.06	0.16
10	99.74	99.50	99.67	99.51	99.65	99.61	0.10	0.11	0.05	0.13

Table 14: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered bunker oil from duck feather using de-oiler (BD1) as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates					F%(mean)	S	%CV	SE	95%
1	32.20	31.16	29.60	33.71	17.02	28.74	6.72	23.39	3.01	8.34
2	57.37	56.53	58.86	64.18	56.14	58.62	3.28	5.60	1.47	4.07
3	72.93	71.33	74.16	76.49	75.56	74.09	2.06	2.78	0.92	2.55
4	82.11	78.48	77.12	82.50	85.64	81.17	3.40	4.19	1.52	4.22
5	89.33	86.59	87.48	89.76	91.22	88.88	1.85	2.08	0.83	2.29
6	98.51	98.38	97.83	99.07	98.75	98.51	0.46	0.47	0.21	0.57
7	99.21	99.41	98.99	99.38	99.55	99.31	0.22	0.22	0.10	0.27
8	99.53	99.74	99.46	99.73	99.75	99.64	0.13	0.13	0.06	0.17
9	99.69	99.80	99.69	99.89	99.84	99.78	0.09	0.09	0.04	0.11
10	99.75	99.82	99.71	99.90	99.87	99.81	0.08	0.08	0.03	0.10

Table 15: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered bunker oil from duck feather using Canola oil as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates					F%(mean)	S	%CV	SE	95%
1	27.51	30.44	30.33	26.01	18.28	26.51	4.98	18.78	2.23	6.18
2	59.83	62.68	63.82	59.13	49.21	58.93	5.77	9.79	2.58	7.17
3	71.93	74.57	73.88	72.61	75.56	73.71	1.46	1.99	0.65	1.82
4	82.31	80.34	79.51	83.73	80.53	81.28	1.70	2.10	0.76	2.12
5	84.66	92.40	87.75	88.13	89.64	88.51	2.83	3.19	1.26	3.51
6	97.55	96.73	97.26	97.71	98.77	97.60	0.75	0.77	0.34	0.94
7	98.77	98.31	98.89	99.12	99.32	98.88	0.38	0.39	0.17	0.47
8	99.30	98.95	99.39	99.37	99.64	99.33	0.25	0.25	0.11	0.31
9	99.53	99.14	99.58	99.62	99.80	99.54	0.24	0.24	0.11	0.30
10	99.60	99.35	99.68	99.65	99.85	99.63	0.18	0.18	0.08	0.22

Table 16: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered bunker oil from duck feather using blended oil (canola/soybean) as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates					F%(mean)	S	%CV	SE	95%
1	23.20	31.21	33.68	27.01	18.28	26.67	6.17	23.13	2.76	7.66
2	51.52	56.65	62.74	60.20	49.21	56.06	5.69	10.15	2.55	7.07
3	65.96	76.24	71.48	69.02	75.56	71.65	4.35	6.07	1.95	5.40
4	75.92	85.55	81.75	80.86	80.53	80.92	3.44	4.25	1.54	4.27
5	85.32	90.81	90.74	91.75	89.64	89.65	2.53	2.83	1.13	3.15
6	94.48	95.14	97.80	97.81	96.77	96.40	1.53	1.59	0.68	1.90
7	96.89	97.46	98.57	99.01	99.13	98.21	0.99	1.01	0.44	1.23
8	97.44	98.03	99.21	99.44	99.64	98.75	0.96	0.98	0.43	1.20
9	98.30	98.21	99.48	99.52	99.80	99.06	0.75	0.76	0.33	0.93
10	99.01	98.32	99.63	99.48	99.85	99.26	0.61	0.61	0.27	0.75

Table 17: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered bunker oil from duck feather using methyl oleate as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates					F%(mean)	S	%CV	SE	95%
1	28.34	19.88	34.72	24.07	32.58	27.92	6.07	21.76	2.72	7.54
2	56.77	54.01	70.92	54.44	57.63	58.75	6.97	11.86	3.12	8.65
3	68.79	75.51	81.06	81.74	80.69	77.56	5.50	7.09	2.46	6.82
4	80.70	88.78	89.93	83.29	83.32	85.20	3.96	4.64	1.77	4.91
5	85.58	91.73	92.37	89.61	88.51	89.56	2.72	3.03	1.22	3.37
6	98.58	98.55	99.26	97.99	99.15	98.71	0.51	0.52	0.23	0.64
7	99.67	99.36	99.64	99.29	99.39	99.47	0.17	0.17	0.08	0.21
8	99.85	99.76	99.79	99.85	99.90	99.83	0.06	0.06	0.03	0.07
9	99.89	99.88	99.90	99.78	99.84	99.86	0.05	0.05	0.02	0.06
10	99.87	99.85	99.86	99.96	99.97	99.90	0.06	0.06	0.03	0.07

Table 18: Experimental data and statistical analysis of the magnetic removal, F (%), of weathered bunker oil from duck feather using Bio-dispersol as a pre-conditioner (applied at N =6). Experiments were conducted in five replicates at ca. 22^{o}C.

N	Five replicates					F%(mean)	S	%CV	SE	95%
1	27.01	29.01	27.26	18.12	34.44	27.17	5.88	21.63	2.63	7.29
2	71.96	63.84	61.14	58.25	56.73	62.38	6.01	9.63	2.69	7.46
3	75.42	83.53	74.26	76.56	68.10	75.58	5.52	7.31	2.47	6.85
4	86.64	89.80	79.66	89.39	86.37	86.37	4.06	4.70	1.82	5.04
5	90.28	91.44	84.84	90.76	92.88	90.04	3.07	3.40	1.37	3.81
6	98.45	96.58	96.26	98.57	98.02	97.57	1.08	1.11	0.48	1.34
7	99.19	99.34	99.47	99.18	99.28	99.29	0.12	0.12	0.05	0.15
8	99.41	99.88	99.68	99.49	99.49	99.59	0.19	0.19	0.09	0.24
9	99.68	99.86	99.80	99.76	99.62	99.74	0.09	0.09	0.04	0.12
10	99.82	99.92	99.92	99.86	99.83	99.87	0.05	0.05	0.02	0.06

Table 19. Relative average values of N_{99} for the six pre-conditioners tested compared to the average N_{99} value in the absence of a pre-conditioner.

	No pre-conditioner	Blended oil	Olive oil	Canola oil	Bio-dispersol	De-oiler (BD1)	Methyl oleate
Replicate 1	8.20	6.90	7.10	6.10	6.20	6.00	5.90
Replicate 2	10.00	7.00	7.20	6.80	6.30	6.10	6.00
Replicate 3	10.30	7.60	7.80	7.10	6.60	6.20	6.10
Replicate 4	11.40	10.00	8.10	7.30	6.80	6.20	6.20
Replicate 5	14.60	12.30	8.50	8.20	6.80	7.10	6.50
Mean	**10.90**	**8.76**	**7.74**	**7.10**	**6.54**	**6.32**	**6.14**
S	2.37	2.34	0.59	0.76	0.28	0.44	0.23
SE	1.06	1.05	0.27	0.34	0.12	0.20	0.10

Table 20: Relative values of k_B for the six pre-conditioners tested compared to the k_B value in the absence of a pre-conditioner.

	Bunker oil	
	k_B	SE (k)
No pre-conditioner	0.722	0.101
Olive oil	1.092	0.027
Blended oil	0.877	0.036
Canola oil	1.021	0.039
Bio-dispersol	0.944	0.105
De-oiler (BD1)	1.256	0.109
Methyl oleate	1.186	0.12

Table 21: Comparison between crude oil and bunker oil with respect to the N_{99} and k values for different pre-conditioners and without pre-conditioner.

	N99 (crude oil)		k (crude oil)		N99 (bunker oil)		k (bunker oil)	
	N_{99}	SE	k_C	SE	N_{99}	SE	k_B	SE
No pre-conditioner	9.62	0.93	0.635	0.047	10.9	1.06	0.722	0.101
Olive oil	6.82	0.16	1.270	0.148	7.74	0.27	1.092	0.027
Blended oil	6.56	0.25	1.262	0.081	8.76	1.05	0.877	0.036
Canola oil	6.38	0.24	1.451	0.060	7.1	0.34	1.021	0.039
Bio-dispersol	6.46	0.15	1.606	0.147	6.54	0.12	0.944	0.105
De-oiler (BD1)	5.68	0.21	1.236	0.068	6.32	0.2	1.256	0.109
Methyl oleate	6.08	0.15	1.679	0.201	6.14	0.1	1.186	0.12

Table 22: The relative values of E for the six pre-conditioners and no pre-conditioner in the magnetic cleansing of weathered oil (crude and bunker) from feathers.

	No pre-conditioner	Blended oil	Olive oil	Canola oil	Bio-dispersol	de-oiler (BD1)	Methyl oleate
E (crude oil)	0.000	0.318	0.291	0.337	0.328	0.410	0.368
SE	0.000	0.104	0.099	0.103	0.099	0.103	0.099
E (bunker oil)	0.000	0.196	0.290	0.349	0.400	0.420	0.437
SE	0.000	0.154	0.103	0.108	0.099	0.102	0.099

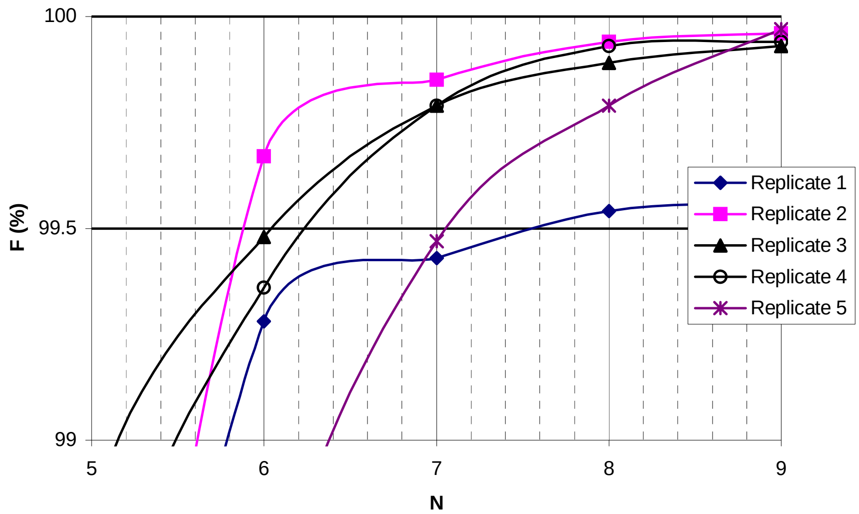


Figure 1: The number of treatment needed for each replicate in the removal of 99% weathered crude oil from duck feathers using de-oiler (BD1) as a pre-conditioner.

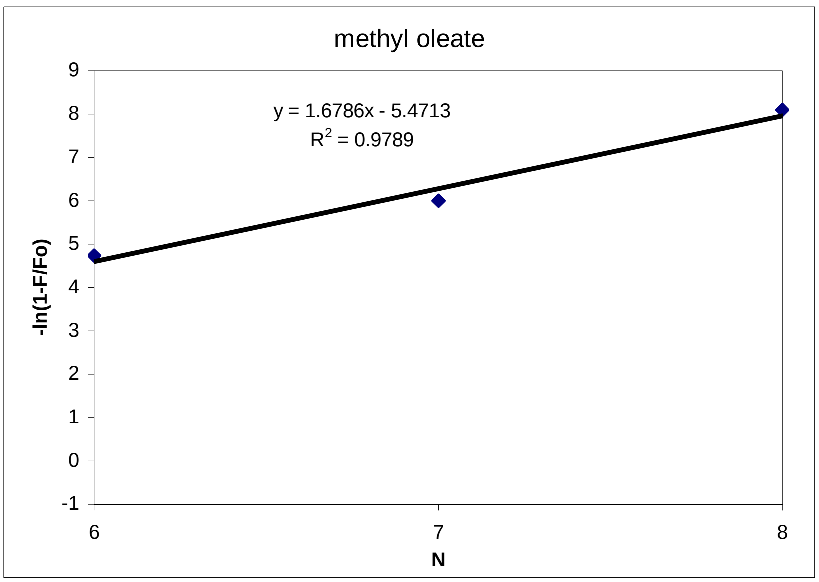


Figure 2: Plot of -ln(1 - F/F_o) versus the number of treatments, N, for the removal of weathered crude oil from duck feathers using methyl oleate as a pre-conditioner.

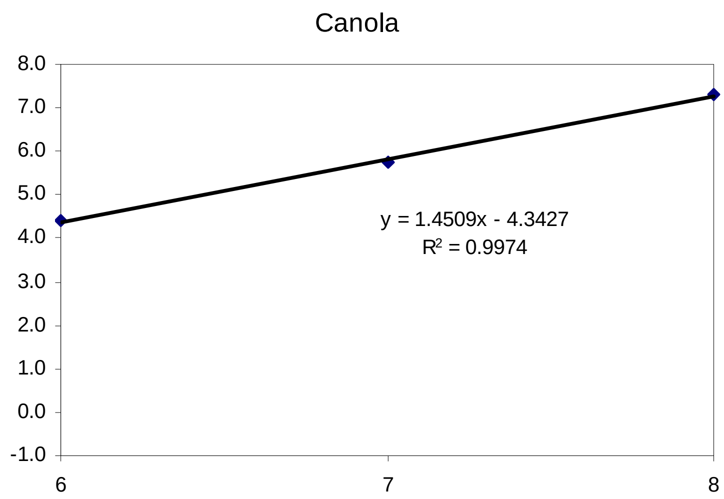


Figure 3: Plot of -ln(1-F/F_o) versus the number of treatments, N = 6 onwards, for the removal of weathered crude oil from duck feathers using Canola oil as a pre-conditioner.

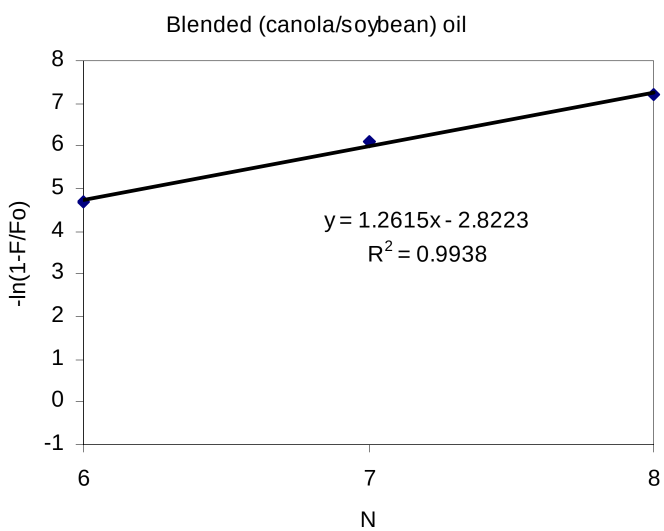


Figure 4: Plot of -ln(1-F/F_o) versus the number of treatments, N = 6 onwards, for the removal of weathered crude oil from duck feathers using blended oil as a pre-conditioner.

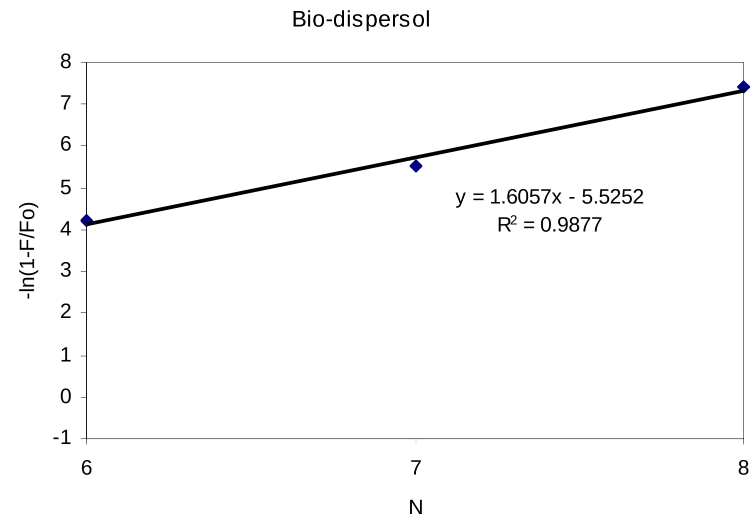


Figure 5: Plot of -ln(1-F/F_o) versus the number of treatments, N = 6 onwards, for the removal of weathered crude oil from duck feathers using Bio-dispersol as a pre-conditioner.

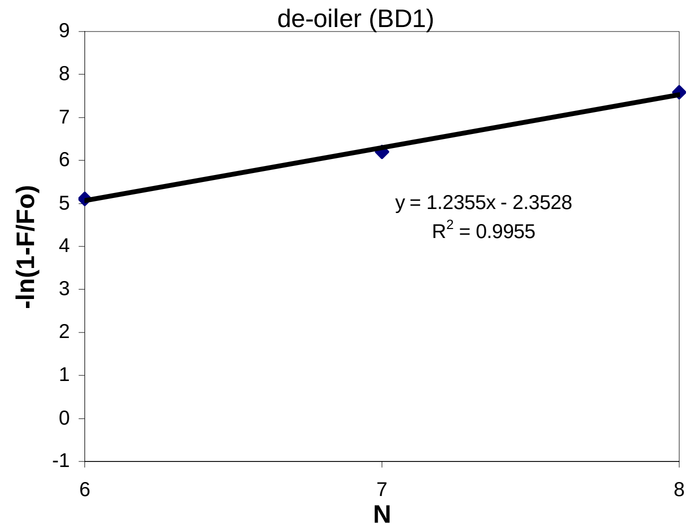


Figure 6: Plot of -ln(1-F/F_o) versus the number of treatments, N (N = 6 to 8) for the removal of weathered crude oil from duck feathers - using de-oiler (BD1) as a pre-conditioner.

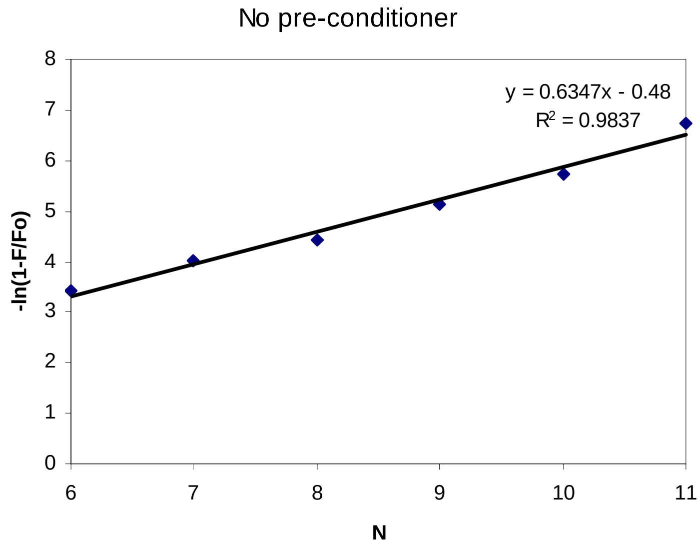


Figure 7: Plot of -ln(1-F/F_o) versus the number of treatments, N (N = 6 to 8) for the removal of weathered crude oil from duck feathers – without using pre-conditioner.

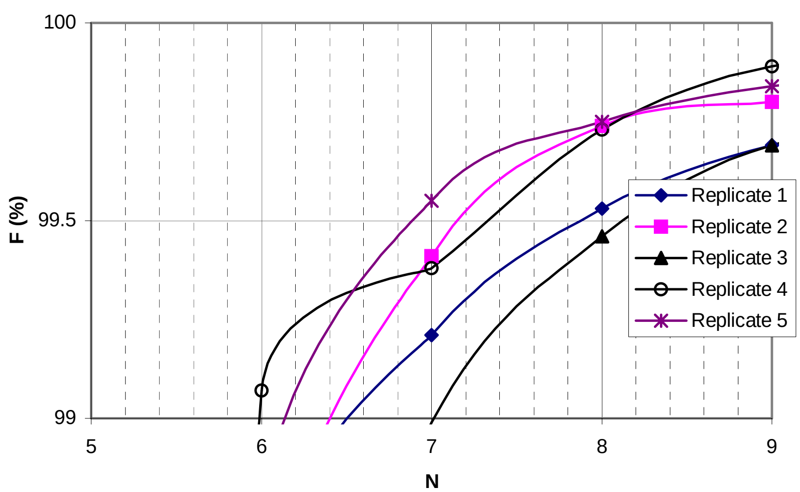


Figure 8: The number of treatment needed for each replicate in the removal of 99% weathered bunker oil from duck feathers using de-oiler (BD1) as a pre-conditioner.

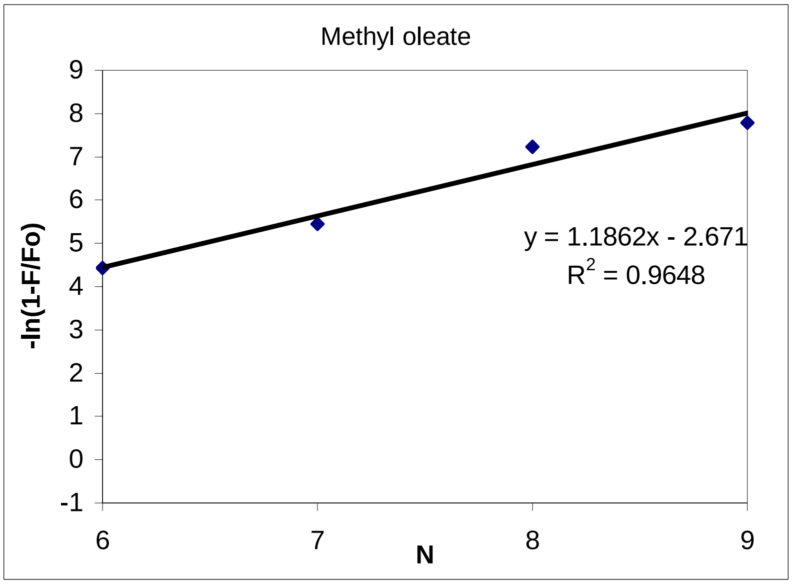


Figure 9: Plot of -ln(1 - F/F_o) versus the number of treatments, N, for the removal efficiency of weathered bunker oil from duck feathers using methyl oleate as a pre-conditioner.

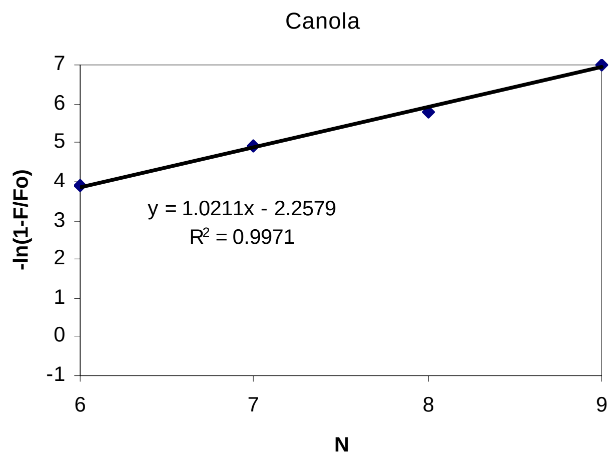


Figure 10: Plot of -ln(1-F/F_o) versus the number of treatments, N =6 onwards, for the removal of weathered bunker oil from duck feathers using Canola oil as a pre-conditioner.

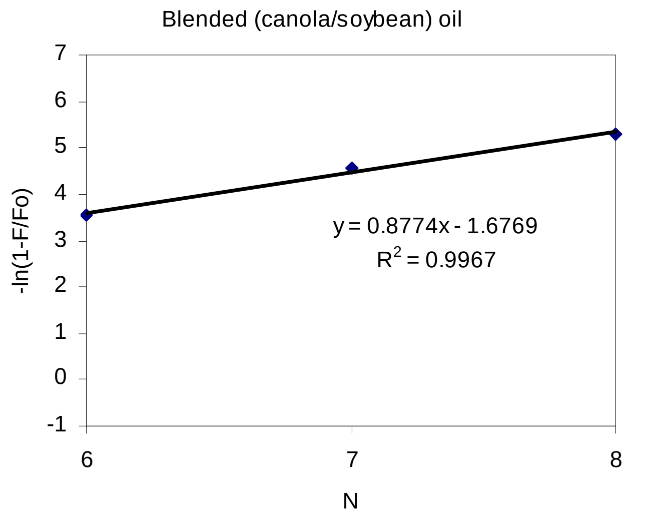


Figure 11: Plot of -ln(1-F/F_o) versus the number of treatments, N =6 onwards, for the removal of weathered bunker oil from duck feathers using blended oil as a pre-conditioner.

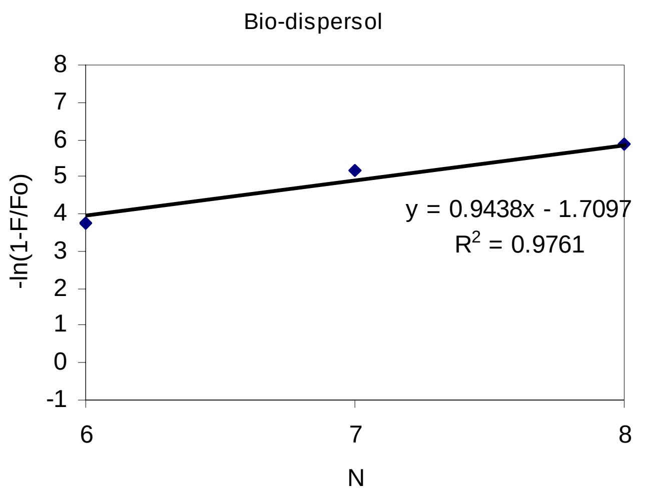


Figure 12: Plot of -ln(1-F/F_o) versus the number of treatments, N =6 onwards, for the removal of weathered bunker oil from duck feathers using Bio-dispersol as a pre-conditioner.

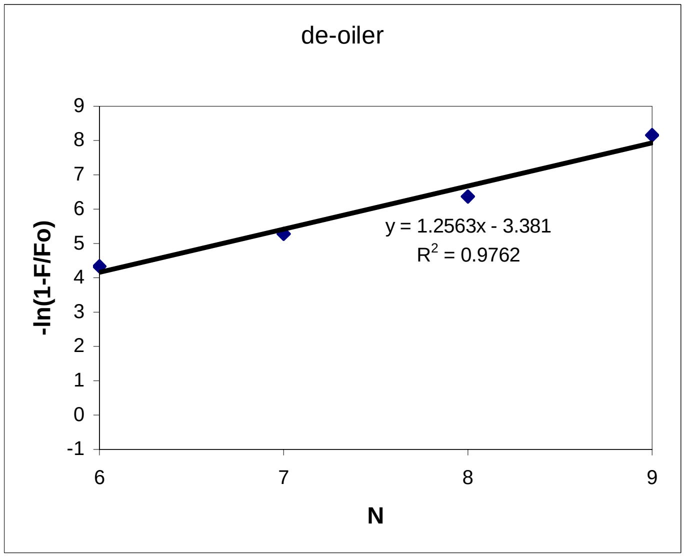


Figure 13: Plot of -ln(1-F/F_o) versus the number of treatments, N (N = 6-9) for the magnetic removal efficiency of weathered bunker oil from duck feathers, using de-oiler (BD1) as a pre-conditioner.

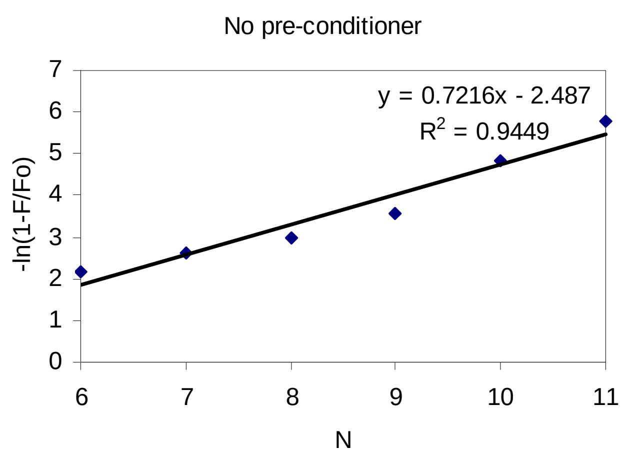


Figure 14: Plot of -ln(1-F/F_o) versus the number of treatments, N (N = 6-11) for the magnetic removal efficiency of weathered bunker oil from duck feathers, without using pre-conditioner.