Combined Fields (Electro-osmosis and Pressure) Dewatering of Kelp

by

Dennis G. Lightfoot

Department of Agricultural Engineering
Macdonald Campus of McGill University
Ste. Anne de Bellevue, Quebec

November, 1991

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The world's brown marine algae, or kelps, have a great potential for agricultural use. Over 14 million tonnes of kelp are estimated to be available for harvesting every year, but only 6.3% is harvested, mostly for food products or alginate extraction. The inclusion of kelp in an animal's ration has been found by several researchers to have a beneficial effect on the animal's health and productivity. High concentrations of kelp in an animal's ration, however, can have detrimental effects on the animal's health due to toxic levels of certain inorganic salts.

By including a dewatering operation in the production of dried kelp meal, much of the soluble salts present in the kelp will be removed with the filtrate. The filtrate would also be valuable as a source of potassium, trace minerals, and phyto-hormones for crops. Energy costs for dewatering are also much lower than for drying. Because kelp is difficult to dewater using conventional methods, a combined fields technique using electro-osmosis and mechanical pressure was investigated.

Electric current and pressure were both found to have a significant positive effect on dewatering. Dewatering resulted in significantly lower ash and available carbohydrate fractions, while having no other significant effect on kelp meal composition. The combined fields dewatering resulted in significant total energy savings over conventional dewatering or drying alone.

The combined fields dewatering process was successfully scaled up to a continuous process using a prototype roller press. The press was able to produce a press cake with up to 32% solids. The continuous process resulted in significantly lower ash content and significantly higher protein. The total energy to produce kelp meal with the roller press was found to be about half of the energy required for drying alone.

RESUME

Les algues brunes, ou varechs, que l'on retrouve partout sur la planète, ont un grand potentiel pour l'agriculture. La récolte annuelle potentielle d'algues brunes a été estimée à 14 millions de tonnes mais seulement 6.3% est actuellement récolté, principalent pour la consommation humaine our l'extraction d'algine. L'ajout d'algue dans la ration alimentaire d'un animal estconsidéré, par plusieurs chercheurs, comme érant bénéfique aussi bien pour la santé de l'animal que pour sa productivité. Par contre une trop grande concentration d'algues dans la ration d'un animal peut avoir des effets négatifs sur sa santé à cause du niveau toxique de certains sels inorganiques.

En ajoutant une opération d'extraction d'eau au cours de la production d'algues séchées, la majorité des sels solubles seront extraits avec la filtrat. Le filtrat pourrait aussi être utile et tant aue source de potassium, oligo-éléments et phythormones. Les coûts énergétiques d'extraction d'eau sont aussi bien moindres que ceux de séchage. Puisque l'extraction d'eau des algues est difficile et utilisant des methodes conventionnelles, une méthode combinant l'éctro-osmose et la pression méchanique a été étudiée.

Il a été remarqué que la force du champ électrique et la pression, avaient des effets positifs sur l'extraction d'eau. Les seuls effets significatifs de l'extraction d'eau sur la composition finale de l'algue déshydratée sont la réduction de la proportion de cendres et de celle des différents hydrates de carbone digestibles. La méthode combinée d'extraction d'eau a permis de réaliser une économie d'energie significative comparativement à l'extraction d'eau conventionnelle ou au séchage seulement.

En utilisant une presse à rouleaux, la méthode combinée d'extraction d'eau a été reproduite pour obtenir un procédé continu. La presse pouvait produire un pain avec un maximum de 32% de matière sèche. Le procédé continu a résulté, de façon significative, en une diminution de la proportion de cendres et en une aumentation de la proportion de protéines. La quantité totale d'energie nécessaire pour produite des algues séchées en utilisant la press à rouleaux était la moitié de celle requise lorsque seulement un séchoir est utilisé.

ACKNOWLEDGEMENTS

I would like to express by sincere appreciation to all who contributed toward this project in any way. In particular, I would like to thank my thesis supervisor Dr. G. S. V. Raghavan for his support and encouragement, my parents [illegible] Joan Lightfoot for harvesting and shipping kelp for the laboratory experiments and for their contributions towards the finished roller press, to André Lapierre for translating the abstract, and to Maria Elena Ruthman for her continuous personal support through the duration of this project.

I would also like to thank the Natural Sciences and Engineering Research Council for their financial support through their post-graduate fellowship and operating grants program. I would also like to thank Martinex Science Inc. for the funding needed to continue this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The world's brown marine algae, or kelps, are a vast unused resource which could potentially play an important role in the agriculture of the future. The potential annual harvest of kelp species is estimated to be over 14 million tonnes, but only 6.3% of this is harvested (Waaland, 1981). Over 500,000 tonnes of *Nereocystis luetkeana*, or bull kelp, grow off of the coast of British Columbia alone (Foreman, 1983), and virtually none of this is harvested. The composition of *Nereocystis luetkeana* gives it great potential for the production of animal feed or foliar spray fertilizers and growth stimulants for terrestrial plants.

Marine algae has been used since ancient times in coastal areas as emergency livestock feed or as feed additives. The inclusion of dried seaweed meal in an animal's ration has been demonstrated by several researchers to have beneficial effects on the health and productivity of the animals. Researchers have also found, however, that the inclusion of large amounts of seaweed have detrimental effects due to the high concentration of certain salts in the plants.

Aqueous extracts of different kelp species have been investigated as foliar spray fertilizers and growth stimulants. The seaweed extracts were found to improve yields of several crops, give longer storage life, and reduce the damage due to certain pests and diseases. The effects of kelp extracts on terrestrial plants has been attributed to the presence of phytohormones and trace minerals in the extracts.

If a dewatering process were included in the manufacture of dried seaweed meal, energy costs would be less than for drying alone. Because water would be removed in the liquid phase, some soluble salts would also be removed, improving the quality of the seaweed meal. The filtrate removed by dewatering could then be used as an aqueous seaweed extract fertilizer or growth stimulant.

Because kelp has been found to be difficult to dewater using conventional mechanical techniques, a combined fields approach will be investigated. Combined fields dewatering uses more than one property of the solid-liquid mixture to effect separation. In this thesis, mechanical pressure will be used in combination with electro-osmosis to dewater *Nereocystis luetkeana* fronds.

II. OBJECTIVES

1. To determine the effects of combining different levels of physical pressure and electric current for dewatering kelp. The effects on the amounts and composition of filtrate and press cake material produced are to be determined.

2. To develop a continuous combined fields dewatering process using electro-osmosis and physical pressure to dewater kelp.

3 From the dewatering process, to produce two potentially valuable products:

   a) A superior kelp meal feed from the press cake, which will be lower in salts and will be produced with less energy than other existing kelp meal feeds.

   b) A foliar spray fertilizer and growth stimulant for terrestrial plants from the filtrate.

III. LITERATURE REVIEW

3.1 The Brown Algae Resource

Over 14 million tonnes of brown algal seaweed, or kelp, are estimated to be available for harvesting every year (Waaland, 1981). Figure 3.1 shows the distribution of the resource over the different ocean coasts, along with actual recent harvests. As can be seen from the figure, very little (6.3%) of the potential is being utilized. Two areas where significant harvesting does take

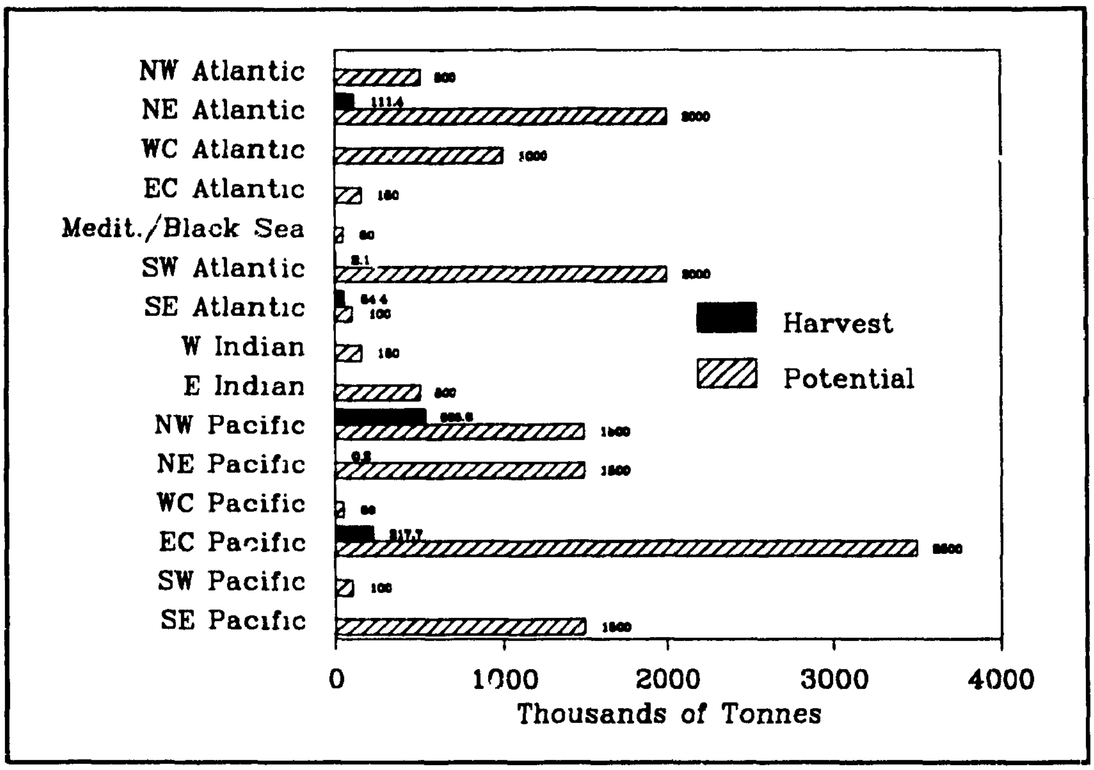

Figure 3.1. Recent and estimated potential harvests of brown algae (Waaland, 1981).

place are the north-west Pacific, where most of the harvest is used for human food, and the east-central Pacific, where most of the harvest is used for algin extraction.

Algin extraction is currently the second most extensive use of the brown algae resource (Waaland, 1981), as shown in Figure 3.2. Algin is used as a binder, stabilizer, and emulsifier in industries as diverse as food, textiles, printing, pharmaceuticals, and cosmetics. The largest use of brown algae is for direct human consumption, although this use is restricted almost exclusively to the western Pacific countries.

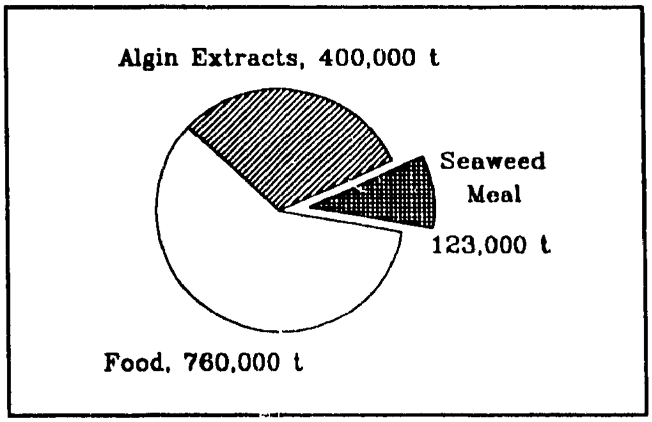

Figure 3.2. Present uses of brown algae (Waaland, 1981).

Less than 10% of the annual kelp harvest is made into dried seaweed meal. Some of the meal is later processed for algin extraction, while much of the remainder is used in animal feeds. The use of brown seaweeds for animal feeds was stated in the 1970's to be the present use with the greatest potential for expansion (Jensen, 1977). The benefits of including seaweed meal in an animal's ration have been demonstrated, and increasing cost of land produced feeds should soon make the seaweed feeds an economic alternative.

A small fraction of the annual kelp harvest is used as a fertilizer or growth stimulant for terrestrial plants. This use also has great potential for growth, especially with the recent popularity of organic and sustainable agricultural practices.

3.2 Seaweed as an Animal Feed

Seaweed has long been used as an animal feed or feed supplement in coastal areas when more conventional feeds have been scarce. Seaweeds were used as emergency livestock rations by the Greeks and Romans as long ago as 46-43 B. C. (Waaland, 1981). Seaweeds have also been used along the coasts of France, Scotland, Iceland, and Norway for centuries as a feed supplement for sheep, cows, and pigs (Jensen, 1971).

The inclusion of different seaweeds at different concentrations in the diets of farm animals has been studied over the last century, yielding apparently inconsistent and conflicting results. It is evident from the literature, however, that seaweed has the greatest potential for ruminants, while its use would likely be restricted to a mineral and vitamin supplement for non-ruminants which would have difficulty digesting much of the organic matter and protein (Whyte and Englar, 1975).

3.2.1 Sheep

Tribe and Tribe (1949) studied the eating habits of a rare breed of Orkney sheep which graze almost exclusively on seaweeds washed up on the shore of North Ronaldshay Island, Scotland. It was noted that the sheep were very selective in the species eaten and in the parts of the individual plants eaten. Laminariales were preferred, especially *Laminaria digitata*, over the Fucales, and the fronds of the plants were selected over the stipes. An apparent correlation between palatability and digestibility was also noted.

Senior *et al.* (1946) studied the digestibilities of some different seaweeds by two adult male sheep. Digestibilities of dry matter and organic matter ranged from 28.9 to 66.6% and 29.3 to 65.7% respectively. The higher digestibilities consistently came from the Laminariales, while the Fucales showed inferior digestibility. The protein in all of the seaweed studied was found to be indigestible, and the seaweed was even found in some cases to have a detrimental effect on the digestibility of the protein from the other constituents in the ration, possibly due to the high ash content of the seaweed which causes some elements to exceed toxic levels.

Jensen (1971) conducted a large-scale feeding trial with sheep on 67 Norwegian farms to determine the effect of seaweed meal (*Ascophylum nodosum*) in the diet of sheep. An increase of winter wool corresponding to 3.3% for all test ewes was reported, and a 20% increase for a flock receiving neither herring meal nor mineral supplements was observed. The seaweed supplement also significantly reduced the number of lambs lost to white muscle disease, and growth rates of the lambs were higher.

Herbert *et al.* (1978) performed a study involving Scottish Blackface and Welsh Mountain sheep fed 0, 5, or 15% dried seaweed meal (*Ascophylum nodosum*) in their ration. No adverse effects to feed consumption, live weight, or carcass weight were noted, and the seaweed meal was found to have an apparent therapeutic effect when fed to sheep with presumed copper intoxication.

Ratan *et al.* (1979) studied the effect of including seaweed meal (*Sargassum* spp.) in the diets of Nali and Merino x Nali sheep at levels of 10% and 20% of concentrates fed. There was no significant difference in the digestibility of nutrients, feed consumption, or growth rate, although the highest growth rate was observed in the control group.

3.2.2 Cattle

Nebb and Jensen (1965) performed an experiment involving 6 sets of identical twin cows, with both cows receiving identical rations except that the mineral supplement of one twin's ration was replaced by 200 g of fortified seaweed meal (*Ascophylum nodosum*) per day. The milk yield from the seaweed fed animals was 4.5% higher than in the control group, while no effect on reproduction, live weights of calves, mastitis, or other characteristics were noticed.

Jensen (1971) reported similar results from an experiment involving 7 pairs of twin cows over 7 years. Again, 200 g of *Ascophylum nodosum* meal was fed to one twin in the place of the mineral supplement fed to the control animals. The seaweed fed group produced 6.8% more fat corrected milk than the control group. The feeding of seaweed meal also caused a reduction in the number of services required per conception, and a dramatic reduction in the incidence of mastitis.

Desai and Shukla (1975) studied the effects of including 15% or 30% kelp meal (*Sargassum* spp.) in the rations of lactating Kankrej cows. A slight reduction in body weight was observed when cows were fed 30% kelp meal, but was found to be insignificant. No significant differences were observed in milk or fat corrected milk yields or costs between the treatments. It was thus recommended that when conventional feeds are scarce or expensive, seaweed meal could be included in the diet at levels up to 30%.

Jayal *et al.* (1978) found that feeding calves the seaweed residue remaining after alginate extraction had a significant beneficial effect on digestibility of dry matter and carbohydrates. Gain in body weight and feed consumption were found not to be significantly different from control animals.

3.2.3 Swine

Nebb and Jensen (1965) and Jensen (1971) reported the effects of including 3 to 5% *Ascophylum nodosum* meal in the diet of bacon pigs. The seaweed meal was found to have no adverse effects on the rate of weight gain, feed consumption, or food conversion ratio of the pigs. A slight reduction in the thickness of back fat and an increase in the length of carcass was noted for the pigs fed seaweed meal. There was also a large reduction in the number of livers which had to be discarded due to liver parasites.

Whittemore and Percival (1975) found that feeding pigs residue of *Ascophylum nodosum* after alginate extraction as 50% of their ration resulted in diarrhoea within seven days and negative protein digestibility. Beames *et al.* (1977) also found negative protein digestibility for *Nereocystis luetkeana* meal fed to growing pigs. It was suggested that part of the reason for the low digestibility could be the high (46%) ash content of the kelp. They also found, however, that the seaweed had a stimulatory effect on feed intake, and that digestibilities increased with time as the gut microflora adapted to the kelp meal.

Murakami *et al.* (1983) found that pigs fed 20% *Echlonia cava* in their ration showed slightly lower growth rates and higher feed intake and conversion. The quality of the carcasses were found to be equally good, with the seaweed fed group having higher values in length of loin and percentage ham, while the control was higher in dressing percentage, loin area, and thickness of back fat. It was concluded, therefore, that if the cost of seaweed is lower than that of cereal feed, then the seaweed could be economically substituted for some of the cereals. The digestibility of the seaweed was found, however, to decrease with increasing concentration in the ration.

3.2.4 Poultry

Jensen (1971) found that the inclusion of 2 to 5% *Ascophylum nodosum* meal into the diet of chickens and laying hens had no ill effect, while the addition of 3 to 7% to a ration deficient in vitamin A or B-2 or both resulted in a significant increase in growth and egg production. All additions of seaweed meal were found to increase the iodine content of the eggs and give the yolks an agreeable dark colour.

Murakami *et al.* (1983) found that *Echlonia cava* meal, included in a ration at the 10% level, caused slight reductions in body weight compared to the control birds, while 40% inclusion caused dramatic decreases in body weight.

Much of the variability in the reported value of seaweed meal as animal feed is due to differences in the nature of the tests (species of seaweed used, concentration in the diet, and length of time fed). In general, seaweed meal seems to be beneficial in small quantities while large quantities often result in detrimental effects on the digestibility of the kelp and the rest of the ration. Jensen (1971) stated that substances such as salts and tannins influence the digestibility of the meal when seaweed is fed at high concentrations in the diet. Digestibility of the kelp meal was also found to improve with time (Beames *et* *al.*, 1977). This was recognized earlier by Black (1955), who stated that the acquisition of the correct gut microflora for the metabolism of the seaweed carbohydrates is necessary. Orpin *et al.* (1985) found that the microbial populations of the rumens of seaweed-fed Orkney sheep were different, both quantitatively and qualitatively, from those of pasture fed animals of the same breed. Other important variables effecting digestibility are species of seaweed, time of harvest, and composition of the basal ration.

3.3 Seaweed Extracts as Foliar Sprays

Liquid seaweed extracts, produced from brown marine algae, have been studied as fertilizers and growth stimulants for terrestrial plants since the introduction of the first commercially available liquid seaweed fertilizer in around 1950 (Booth, 1965). Booth (1965) reported that the seaweed extract gave better seed germination, better frost resistance, more efficient uptake of nutrients, and better resistance to fungal diseases and insect pests. Higher yields and better storage quality of fruit from plants sprayed with seaweed extract have also been reported.

Blunden (1971) did extensive experimentation to determine the effect of an aqueous seaweed extract on the yields of various crops. He found that the extract increased the yields of bananas, tomatoes, peppers, potatoes, sweet corn, and oranges, and also increased the weight of gladioli corms. Blunden *et al.* (1974) also reported that the seaweed extract increased the yield, sugar content, and clarity of juice from sugar beets. Blunden and Wildgoose (1977) showed that the seaweed extract not only increased the yield of potatoes, but also produced more evenly sized tubers with a smaller undersized fraction. Stephenson (1974) found that a seaweed extract significantly increased the yields of winter wheat, grass, grape vines, celery, and tomatoes, while Povolny (1974) found that growing tomatoes in cellulose pots steeped in diluted aqueous seaweed extract significantly increased plant growth. Nelson and van Staden (1984a) stated that seaweed extract increases plant growth and yield of cucumbers, although an initial inhibition of fruit growth was observed. Nelson and van Staden (1984b and 1986) also found that the seaweed extract causes wheat to have thicker culms and, therefore, to be less prone to lodging, as well as effecting more robust plants and greater grain yields. Temple and Bomke (1989) reported that seaweed extracts increased yields of beans by an average of 24%. Figure 3.3 gives a summary of the effect of seaweed extracts on the yields of different crops.

Povolny (1969) reported that the quality of stored apples was improved if the apples were from trees sprayed with a liquid seaweed extract, although this effect varied greatly with the variety of apple tested. The maturing process of the stored apples was also observed to be delayed. Skelton and Senn (1969) found that spraying peach trees with liquid seaweed extract caused a significant increase in the storage life of the fruit, while causing no significant changes in the composition or quality of the fruit. Blunden (1971) reported a

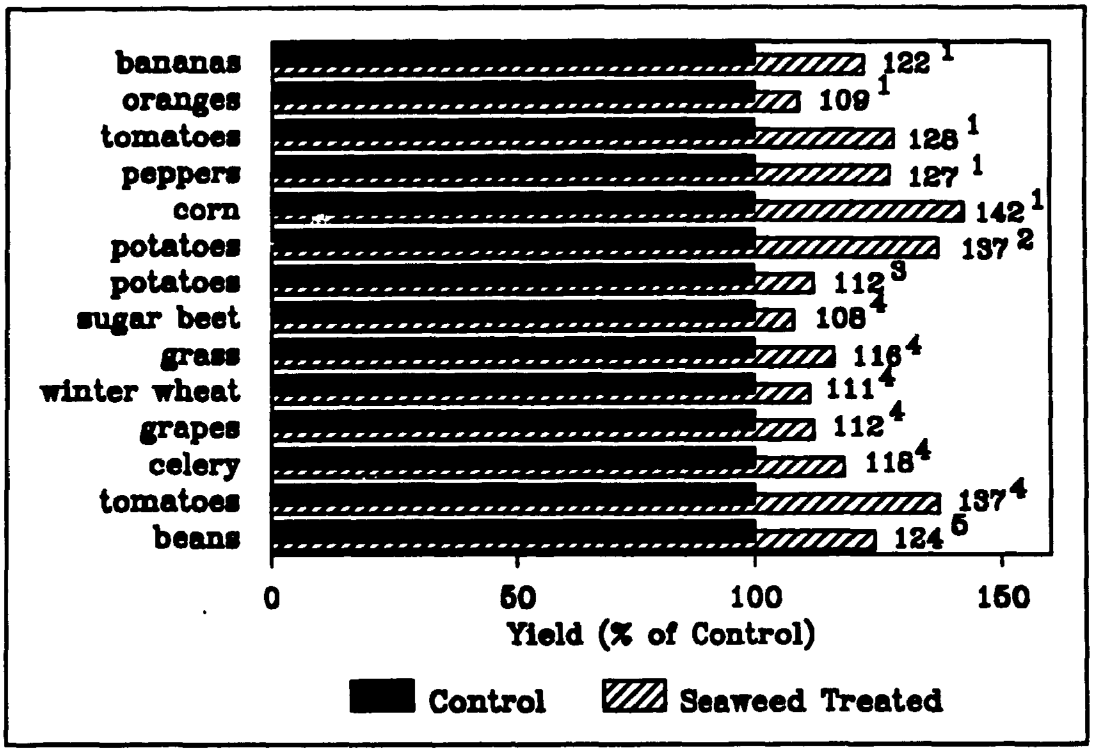

Figure 3.3. Effect of kelp extracts on crop yields ([1]Blunden, 1971; [2]Blunden and Wildgoose, 1977; [3]Blunden et al., 1974; [4]Stephenson, 1974; [5]Temple and Bomke, 1989).

similar increase in storage life for peppers and oranges when plants were sprayed with an aqueous seaweed extract.

Stephenson (1965) reported that liquid seaweed extract was effective at reducing powdery mildew on turnips, grey mould on strawberries, "damping off" of tomato seedlings, and black bean aphid and orchard red spider mite populations. Tarjan (1977) found that seaweed extract was also effective at reducing nematode damage to infested citrus seedlings, while the extracts were found to be ineffective at controlling the nematodes in large mature trees. Featonby-Smith and van Staden (1982) reported that the seaweed extract reduced the damage due to nematodes in tomatoes, although the number of nematodes in the infected soil remained essentially the same. Pracer *et al.* (1987) studied the effects of aqueous extracts of different seaweeds on tomato plants infested with different nematodes and concluded that there was great variability among the seaweeds at reducing the effects of the nematodes, and only one of the seaweeds tested was actually effective as a nematicide.

Seaweed extract was reported by Booth (1965) to have hastened the germination of beet seeds and also gave a 25% increase in germination. Wiczec and Ng (1982) also found that seaweed extract improved the germination of beets.

The beneficial effects of seaweed extracts on terrestrial plants can be partially explained by the presence of growth stimulants, such as gibberellins, auxins, and cytokinins (Brain *et al.*, 1973; Williams *et al.*, 1974; Blunden and Wildgoose, 1976). Temple and Bomke (1989) and Temple *et al.* (1989) detected cytokinin, auxin, and gibberellin activity in kelp extracts. Plant hormones extracted from the seaweed were less effective, however, than the raw kelp concentrate at increasing bean yields. The presence of several trace minerals which may be deficient in the soil and absent in commercial fertilizers has also been suggested as a beneficial factor of the seaweed extracts (Booth, 1968). Temple and Bomke (1989) suggest synergistic effects of the trace minerals when combined with plant hormones.

3.4 Composition of *Nereocystis luetkeana*

Nereocystis luetkeana, or bull kelp, is a large brown marine alga native to the north-east Pacific coast. The alga is an annual canopy forming kelp which constitutes over 90% of the kelp beds off the coast of British Columbia, and yields about 500,000 tonnes per year off the British Columbia coast alone (Foreman, 1983). This kelp grows along rocky coastlines in the upper sub-tidal zone to a depth of several meters, held to the rocks by a branched holdfast. The stipe, or stem, of a mature plant stretches for up to 25 m from the holdfast, where it is a solid cylinder about 10 to 15 mm in diameter, gradually increasing in diameter to a hollow tube which terminates in a spherical float about 150 to 170 mm in diameter. Up to 20 fronds, or leaves, each up to 150 mm wide and 15 m long, are attached to the float in two clusters. Figure 3.4 is a sketch of a single plant.

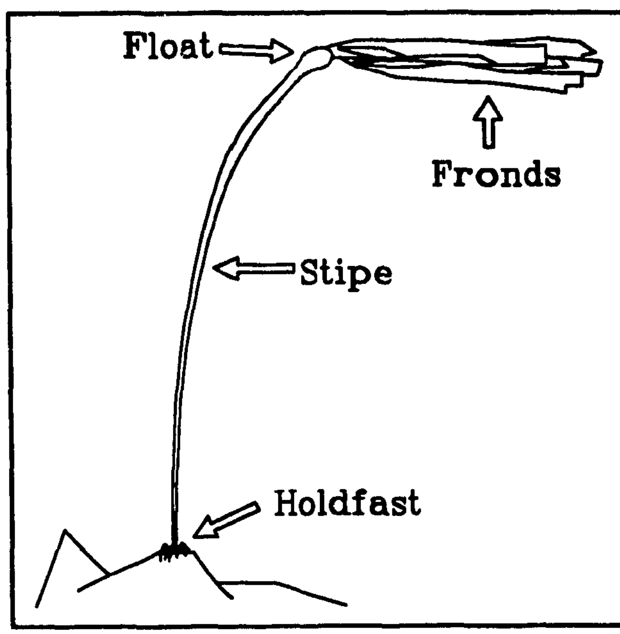

Figure 3.4. Sketch of a single *Nereocystis luetkeana* plant.

The composition of *Nereocystis luetkeana* is similar to that of other brown marine algae, with slightly higher protein and ash contents than

Macrocystis species (Whyte and Englar, 1974a; Whyte *et al.*, 1981; Rosell and Srivastava, 1984). Like other brown algae in the Laminariacea family, the composition of *Nereocystis luetkeana* varies significantly with location and season (Wort, 1955; Whyte *et al.*, 1974; Rosell and Srivastava, 1984), although seasonal variation has been found to be less than that for the Atlantic Laminariales (Whyte and Englar, 1975).

Whyte and Englar (1974a) determined the composition of *Nereocystis luetkeana* fronds and stipes and whole *Macrocystis integrifolia* plants, both species being harvested in early August near Masset, B. C. The results of their analysis are given in Table 3.1. As can be seen, the *Nereocystis luetkeana* fronds have higher water, protein, and ash contents than the *Macrocystis integrifolia*, while the stipes have higher water and ash contents.

Table 3.1. Composition of *Macrocystis integrifolia* and *Nereocystis luetkeana* fronds and stipes (Whyte and Englar, 1974a).

Parameter	*M. integrifolia*	*N. luetkeana* fronds	*N. luetkeana* stipes
Water, %	86.9	92.8	91.9
Ash, % dry wt.	31.2	45.9	51.5
Protein, % dry wt.	11.2	21.5	11.3
Na Alginate, % dry wt.	20.3	19.5	19.6
Sodium, % dry wt.	3.1	6.5	6.8
Potassium, % dry wt.	10.3	13.9	22.7

Whyte and Englar (1974b, 1975) and Whyte *et al.* (1974) studied the seasonal variation in composition of *Nereocystis luetkeana* fronds and stipes from a single kelp bed near Vancouver, B. C. The protein content of the fronds was found to vary from 14.4% in the spring to 10.9% in the late summer and autumn, while ash content of the fronds varied from 48.0% in early spring to 35.9% in midsummer. The protein and ash contents of the stipes followed similar trends, ranging from 5.6 to 8.5% and 46.5 to 60.6% respectively. The variation of other components and individual elements over the growing season are summarised in Table 3.2. It was suggested that the composition of

Table 3.2. Seasonal variation in the constituents of *Nereocystis luetkeana* over the growing season (Whyte *et al.*, 1974).

Component	Fronds		Stipes	
	Average	Range	Average	Range
Water, %	91.6	90.4-94.1	91.4	90.4-92.5
Ash, % dry wt.	40.2	35.9-48.0	51.3	46.5-60.6
Protein, % dry wt.	12.4	10.9-14.4	6.6	5.6- 8.5
Na Alginate, % dry wt.	20.0	18.6-23.3	22.4	15.0-25.8
Sodium, % dry wt.	6.6	5.8- 7.6	4.5	3.8- 5.7
Potassium, % dry wt.	10.7	9.7-11.7	19.1	17.3-22.3
Chloride, % dry wt.	15.1	12.7-17.0	19.3	15.1-26.9

Nereocystis luetkeana gave it good potential as an organic fertilizer or as a feed supplement (Whyte and Englar, 1974b), although it was later reported that due to the relatively intractable nature of the algal protein, it would be more effectively utilized by ruminants (Whyte and Englar, 1975).

A nutritional analysis of *Nereocystis luetkeana* by Barta *et al.* (1981) found a proximate composition similar to earlier studies, as is shown in Figure 3.5. The amino acid profile of the protein from kelp fronds was also determined, and is shown in Figure 3.6. The kelp protein was found to contain significant amounts of each essential amino acid, and an in vitro digestibility of 80%. It was concluded that the kelp protein was of high quality, comparable to that of lean beef or cooked egg.

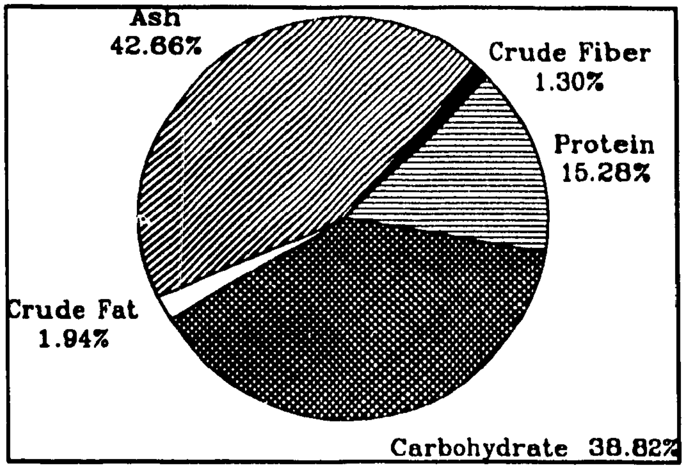

Figure 3.5. Proximate composition of *Nereocystis luetkeana* fronds (Barta *et al.*, 1981).

The results of these previous studies show *Nereocystis luetkeana* to be an excellent source of macro and micro dietary minerals, and a reasonable source of high quality protein. Unfortunately, the use of *Nereocystis luetkeana* as a food or feed is restricted by its excessively high ash content, comprised primarily of water soluble salts, such as chlorides of potassium and sodium. The composition of the soluble ash fraction, however, gives the kelp great

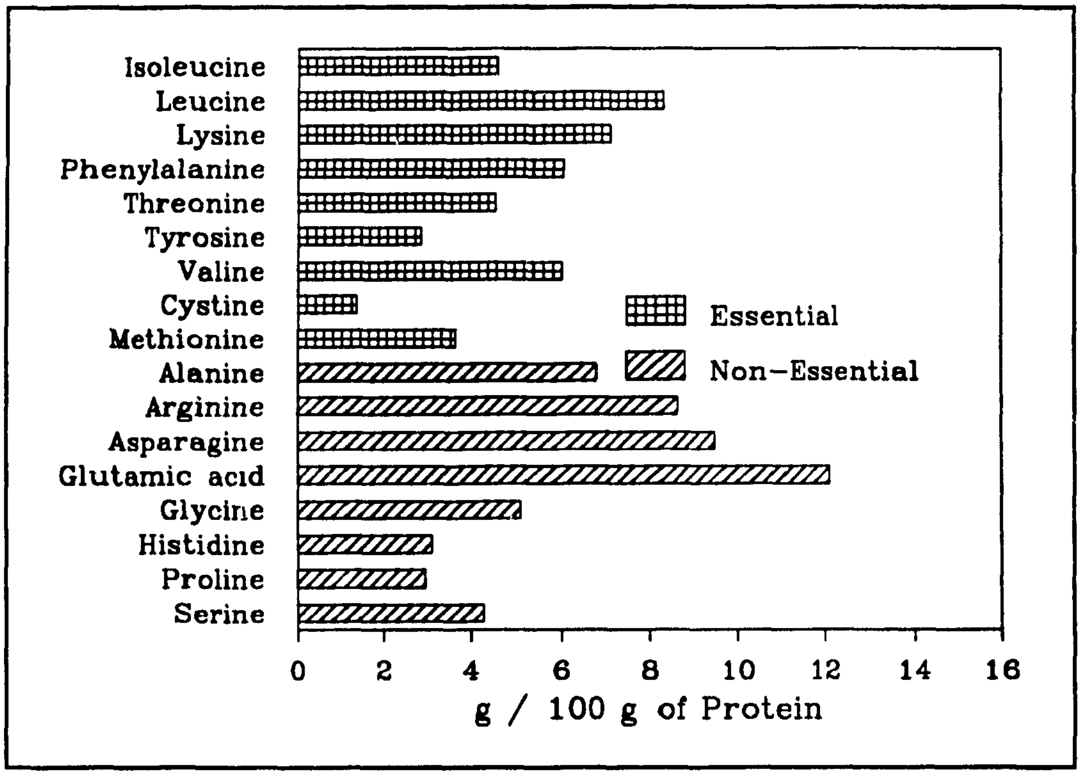

Figure 3.6. Amino acid profile of *Nereocystis luetkeana* frond (Barta *et al.*, 1981).

potential as a source of fertilizer potassium and trace minerals.

Whyte *et al.* (1981) studied the effect of freshwater leeching of minced *Nereocystis luetkeana* and *Macrocystis integrifolia*. The results showed that up to 91% of the kelp ash was soluble and could be leached. Chlorine, potassium, sodium, and boron were the most readily leached elements, while calcium, iron, strontium, zinc, barium, and copper were leached very little. Other elements were soluble to varying degrees. Rosell and Srivastava (1984) also investigated the solubility of different kelp components in different solvents. The solvents tested were distilled water, 0.1 M HCl, and 100% methanol. Water was found to be effective at leaching chloride, mannitol (an algal sugar alcohol), and monovalent cations, such as potassium and sodium, while it was less effective at leaching divalent and trivalent cations. Hydrochloric acid was found to leach nearly all cations, while methanol was ineffective at leaching any part of the kelp.

3.5 Dewatering Kelp

Whyte and Englar (1974a) performed a study to assess the economic feasibility of removing cellular water by pressing prior to drying in a commercial kelp drying operation at Masset, B. C. The dewatering would also remove a portion of the soluble ash fraction from the kelp, making it more suitable as an animal feed. The screw press from a fishmeal pilot plant was used with a press ratio of 6:1. Samples of *Nereocystis luetkeana* and *Macrocystis integrifolia* were minced and pressed in the pilot plant. The presence of phycocolloids such as algin gave the minced kelp a slippery gel-like consistency which made pressing ineffective. *Nereocystis luetkeana* lost only 0.75% of its water on pressing, while *Macrocystis integrifolia* lost only 0.38%. It was concluded that some kind of pretreatment would be necessary if effective dewatering was to take place.

It was later reported by Beleau *et al.* (1975) that pretreatment of minced kelp could facilitate effective dewatering. They found that flushing with a solution of hydrochloric acid, followed by a 150°F hot water blanch would allow pressing of ground California kelp, *Macrocystis pyrifera*, from 88% water by weight down to 40% water using a belt platen press. Hart *et al.* (1977, 1978) found that the addition of 0.5% calcium chloride to ground kelp, in combination with heat treatment, allowed *Macrocystis pyrifera* to be pressed in either a screw press or a belt platen press, removing 75% of the water, 65% of the ash, and only 29% of the organic mater, 38% of the protein, and 1% of the algin. The proximate composition of *Macrocystis pyrifera* before and after dewatering is shown in Figure 3.7.

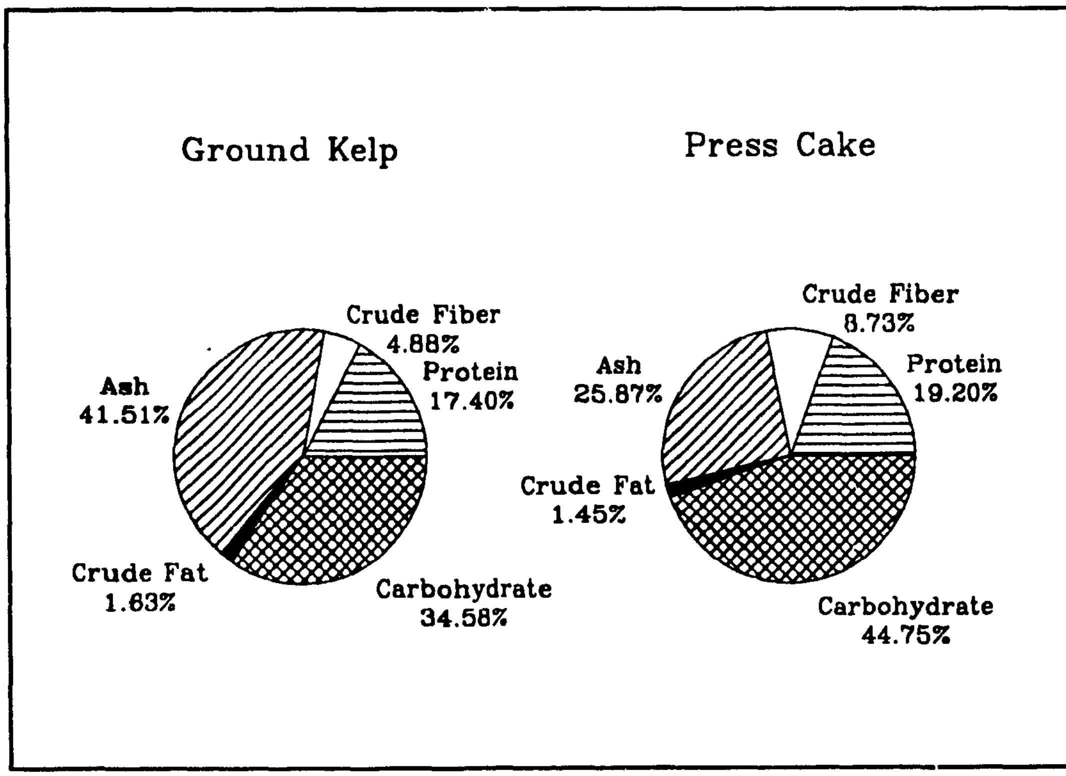

Figure 3.7. Composition of *Macrocystis pyrifera* before and after dewatering (Hart *et al.*, 1977).

A study on the effect of particle size on pressing of ground *Macrocystis pyrifera* (Hart and Kohler, 1986) found that grinding the kelp smaller than 10 mm in diameter gave minimal increases in water and salt removal. The slight increase in water and salt removal was judged not worth the increased energy costs of grinding and increased losses of organic matter.

3.6 Combined Fields Dewatering

Dewatering is a solid-liquid separation process without any accompanying phase change. Because no phase change is involved, energy costs for dewatering are typically much lower than for a drying separation. Energy costs for dewatering alone at very low moisture contents are very high, however, and dewatering is usually followed by drying to produce a final product with the most efficient use of energy.

Most industrial dewatering processes involve the use of a single property or driving force to effect the separation. Typical driving forces include gravity, vacuum or pressure, and centrifugal force. Separations involving other mechanical forces, such as ultrasonics, and non-mechanical forces, such as electric or magnetic fields, are also used in some specialized industries.

It has been realized that the use of two or more driving forces, or fields, simultaneously can be beneficial. The combined fields will tend to act on the system as a whole, as opposed to the generally local or surface effects of typical single property separations (Muralidhara, 1988a, 1988b). Synergistic effects have also been observed when combined fields have been used to dewater a system (Ensminger, 1988; Muralidhara *et al.*, 1988; Muralidhara, 1988b). Proper choice of combined fields for a given system is essential, but a good choice can lead to higher product recovery (solid or liquid), less moisture in press cakes, and lower energy costs (Muralidhara, 1988a).

3.6.1 Electro-osmosis

Electro-osmosis is a dewatering mechanism involving the relative movement of solids and liquids in the presence of a d.c. electric field. The electric field is not only useful for dewatering drained sediments, but also drains them faster (Lockhart, 1983a).

The phenomena of electro-osmosis is caused by an electrical double layer at the walls of capillaries and around suspended particles. Most solids will have a slight electric charge, usually negative, compared to the water and will be attracted to the anode, while water will migrate through the capillaries towards the cathode. The electric potential between the solid and liquid components is called the zeta potential, and is a function of geometry, pH, and ion concentration.

Because electro-osmosis involves the continuous movement of charged particles between electrodes, it is necessary for a certain amount of electric current to be flowing. This current causes electrochemical reactions to take place at the electrodes. At the anode, an oxidation half-reaction takes place,

(1) $M_A \rightarrow M_A^{n+} + ne^-$ or...

(2) $6H_2O \rightarrow 4H_3O^+ + O_2 + 4e^-$.

where M_A is the anode metal and n is its oxidation number. Reaction (2) can be seen simply as the oxidation half of the electrolysis of water. Whether reaction (1) or reaction (2) takes place depends on the anode material. Reaction (1) is generally preferred for all but the most inert metals (Pt, Au, Ag, Pb), while non-metal electrodes, such as carbon or ceramic, will necessitate reaction (2) over reaction (1). This is an important consideration in designing electro-osmotic dewatering apparatus, as the severe oxidizing environment around the anode will corrode most metal electrodes very quickly (Porta, 1986; Lockhart, 1983c, 1986).

At the cathode, a reduction half-reaction takes place, which will be one of the following:

(3) $2H_3O^+ + 2e^- \rightarrow 2H_2O + H_2$

(4) $2H_2O + 2e^- \rightarrow 2OH^- + H_2$

(5) $M^{n+} + ne^- \rightarrow M$

Reaction (3) is generally preferred over (4) due to its lower electrochemical potential, but if insufficient hydronium ion is present, reaction (4) will prevail, causing increased energy requirements and rising pH in the liquid effluent.

Reaction (5) is the electro-deposition of metal onto the electrode surface, and will only take place for nobler metals, such as Cu, Hg, Ag, Au, or Pt (Lockhart, 1986). As can be seen, while the anode reaction depends largely on the anode material, the cathode reaction depends primarily on the cations present in the system (Lockhart, 1983c, 1986).

Electro-osmotic dewatering is particularly effective for mixtures difficult to dewater mechanically, such as fine particle suspensions or gelatinous material (Porta, 1986; Yoshida and Yukawa, 1988a, 1988b; Yukawa *et al.*, 1979). This is because the electro-osmotic flow is relatively independent of pore size (Sunderland, 1988; Yoshida and Yukawa, 1988a).

Yoshida and Yukawa (1988a, 1988b) have developed semi-theoretical design equations for electro-osmotic dewatering of a gelatinous bentonite sludge using either constant d.c. current, or constant d.c. voltage. Under the constant current condition, the volume of water removed from the sludge by electro-osmosis is proportional to the electric current, the time of dewatering, and the zeta potential of the sludge, and inversely proportional to the specific conductivity. If voltage is kept constant, then the volume of water removed from the sludge is proportional to the square root of voltage, the square root of time, and the square root of the zeta potential.

Lockhart (1983b), however, found that the electro-osmotic flow is not usually inversely proportional to the conductivity, nor is it proportional to the zeta potential. In fact, it was found that increasing concentrations of electrolyte in clays caused an increase in flow rate, while energy requirements were comparable or lower to achieve the same percent solids in the press cake (Lockhart, 1983b, 1976). The addition of acid was especially beneficial, as this would allow cathode reaction (3) to be favoured over (4). Clays with high exchangeable calcium and aluminum ions were also found to drain faster than those high in sodium or hydrogen ions (Lockhart, 1983c).

Lockhart (1983a) also studied the effect of voltage on electro-osmotic dewatering of clays. It was found that electro-osmosis is more energy efficient at low voltages, but much quicker at higher voltages. The pH of the separated liquid was also found to rise with applied voltage. Galvanic dewatering, using only the difference in electrochemical potential between two dissimilar electrodes as a driving force was also demonstrated (Lockhart, 1983a, 1986).

Lockhart and Hart (1988) found that electro-osmotic dewatering with current interruptions (ie. electric power switched alternately on and off) could be effective if the collection of water is the rate determining step. If water collection is adequate, however, then current interruptions offer no advantage over continuous electrical power.

A study by Porta (1986) investigated the scale-up aspects of electro-osmotic dewatering, and several recommendations were made for the design of electro-osmotic dewatering equipment. For continuous electro-osmotic dewatering, recommendations included decreasing distance between electrodes in the direction of flow to compensate for increasing resistance of the sludge, and provision for the escape of gasses produced.

Sunderland (1988) developed a continuous dewatering cell for clay. Constant current was the preferred mode of operation, with experimental current densities between 98 and 225 A / m^2. The water removed from the clay by electro-osmosis was found to increase linearly with time and electric current. Acidification of the solid was also observed.

3.6.2 Electro-acoustics

Electro-acoustic dewatering combines electro-osmosis with acoustic dewatering, using ultrasonic vibrations to promote the solid-liquid separation. When electro-osmosis and ultrasonics are used in combination, synergistic effects have been observed (Chauhan *et al.*, 1989; Ensminger, 1988; Muralidhara *et al.*, 1988).

Acoustic energy, in the form of ultrasonic vibrations, have been found to promote solid-liquid separation through various bulk and surface mechanisms. Some of the ways in which ultrasonics can contribute to dewatering are listed below:

1. Attenuation, or absorption, of the acoustic energy leads to heating, which will cause some vaporization, increase the rate of chemical reactions, and lower the viscosity of the fluid.

2. Cavitation can generate free ions, erode or break down susceptible particles, and generate local high temperatures and pressures.
3. The shear wave can cause a change in viscosity of non-Newtonian fluids.
4. Stresses in the press cake can cause fracture, opening new channels for fluid to escape.
5. The vibratory motion will cause a net displacement or rectified diffusion of the liquid through the press cake in the direction of any gradient, such as gravity, pressure, or electric field.
6. Filter surfaces will be kept clean, preventing clogging.

Ultrasonics enhances the effects of electro-osmosis by removing foam produced at the electrodes, by preventing clogging of filters, and by maintaining electrical contact between electrodes and press cake by effecting a more uniform distribution of the conductive fluid. Ultrasonics thus not only increases the rate of dewatering, but also allows the dewatering process to continue to lower moisture contents than would otherwise be possible.

Electro-acoustic dewatering has been demonstrated in the lab for a wide range of dewatering applications (Ensminger, 1988). An attempt at scale-up of electro-acoustic dewatering, adapting electro-osmosis and ultrasonics to a small scale belt press, has also been reported (Chauhan *et al.*, 1989). The belt press was found to give improved separation and lower energy costs than for conventional methods when used to dewater apple pomace or corn fibre slurry.

IV. MATERIALS AND METHODS

4.1 Experimental Dewatering Apparatus

Before any experimentation could begin, apparatus was needed which would allow the simultaneous application of pressure and electric current in varying strengths to a ground kelp sludge for dewatering. Several designs, involving either pneumatic pressure or mechanical pressure, were built, tested and modified before arriving at the final design of the dewatering chamber, which is shown in Figure 4.1.

The earlier designs used metal screens as electrodes. The metal screen was first replaced by a carbon disk for the anode (originally the top electrode), as severe oxidation of the stainless steel screen was observed. After several tests, the cathode screen also showed signs of corrosion, especially near the point where the electrode wire was soldered, causing the cathode screen to be closer to the anode at this point. The cathode was then also replaced by a flat carbon disk, with 28 holes of 5.0 mm diameter drilled through to provide drainage. The wires were fixed to both electrodes using epoxy glue. Dewatering was then found to be better when the current was reversed, so the top electrode became the cathode and the bottom electrode with the drainage holes became the anode (as shown in Figure 4.1). It was assumed that the increased dewatering occurred when electro-osmosis and gravity were working in the same direction, and therefore that the kelp has a positive zeta potential.

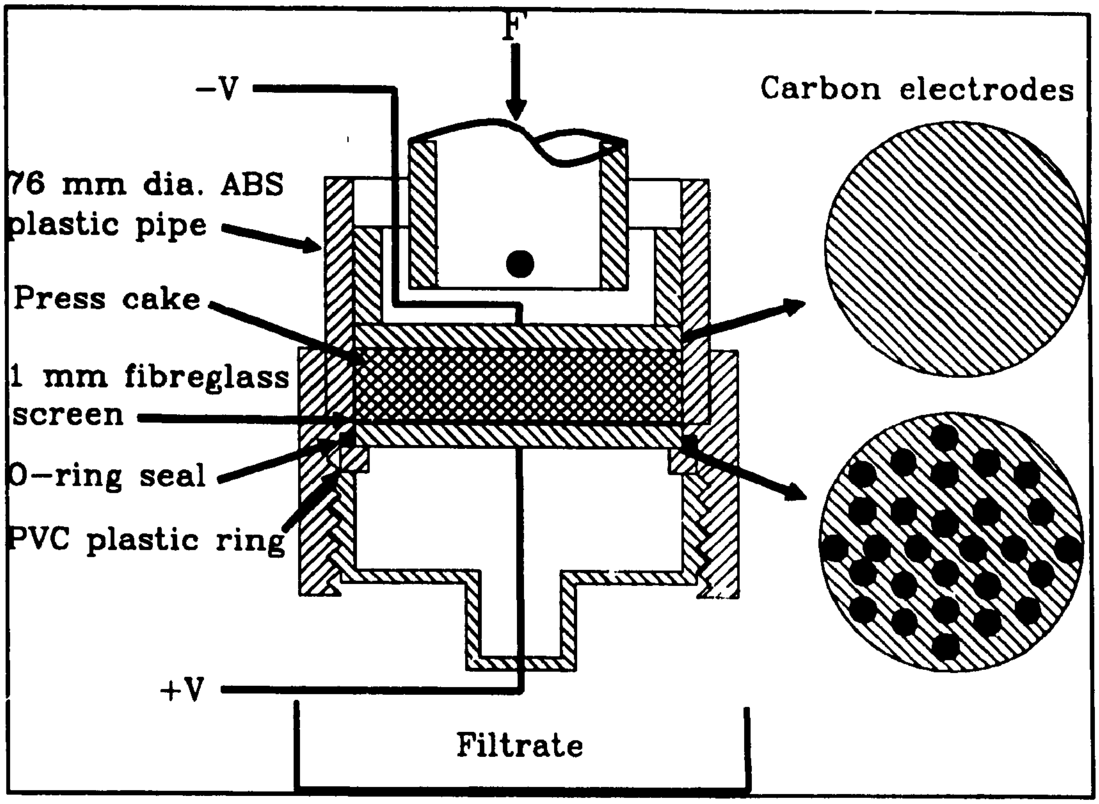

Figure 4.1. Dewatering chamber for combined electro-osmotic and mechanical dewatering.

Electricity was supplied to the electrodes by a B&K 0 - 1 Ampere d.c. power supply operated in constant current mode.

The design uses mechanical pressure, provided by a lever and weight system shown in Figure 4.2. Pneumatic pressure was rejected because preliminary tests showed that after partial dewatering, channels were opened in the press cake which allowed the escape of air at a rate which caused significant pressure loss. The shown lever and weight system provides a compressive force on the press cake of five times the weight suspended from the hanger. The zero-loading condition (with no weights) applies a force of

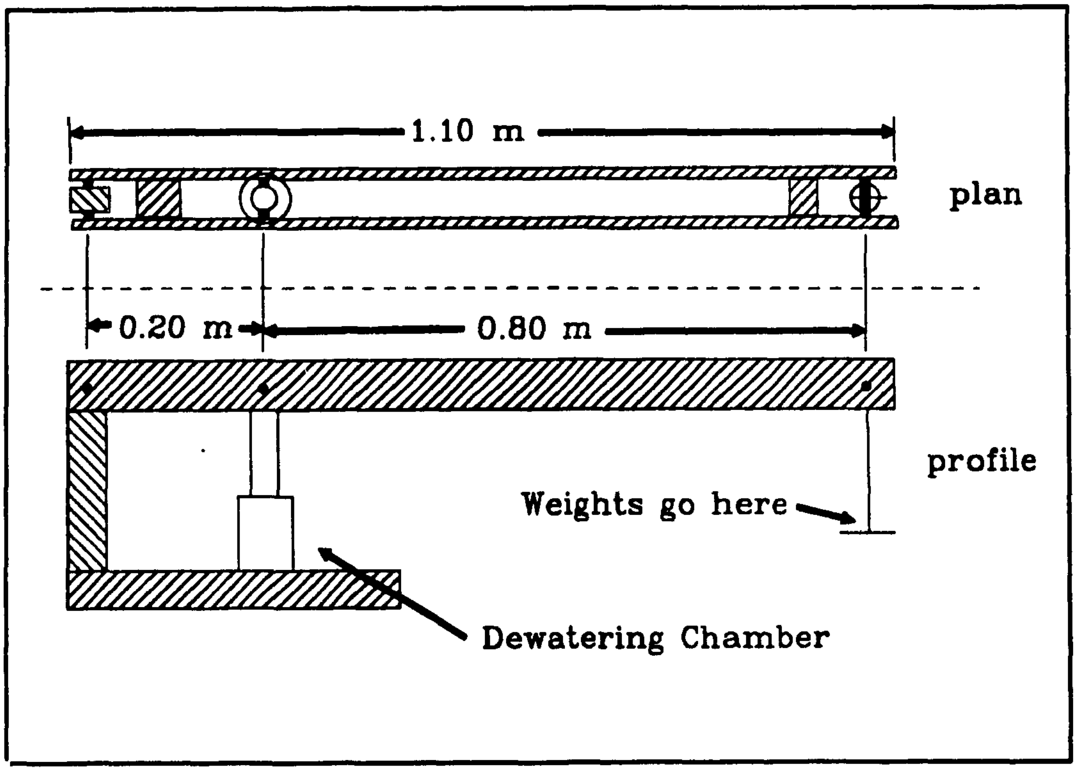

Figure 4.2. Lever and weight system used to apply pressure to kelp in dewatering chamber.

about 34 N (7.46 kPa) from the weight of the beam alone.

Three identical dewatering apparatus were built and operated simultaneously. The electrodes for the three apparatus were connected in series so that the same current would flow through each dewatering chamber.

4.2 Instrumentation

Instrumentation was added to the dewatering apparatus so that energy consumption, both electrical and mechanical, could be measured for each dewatering unit. All measurements were taken periodically during the

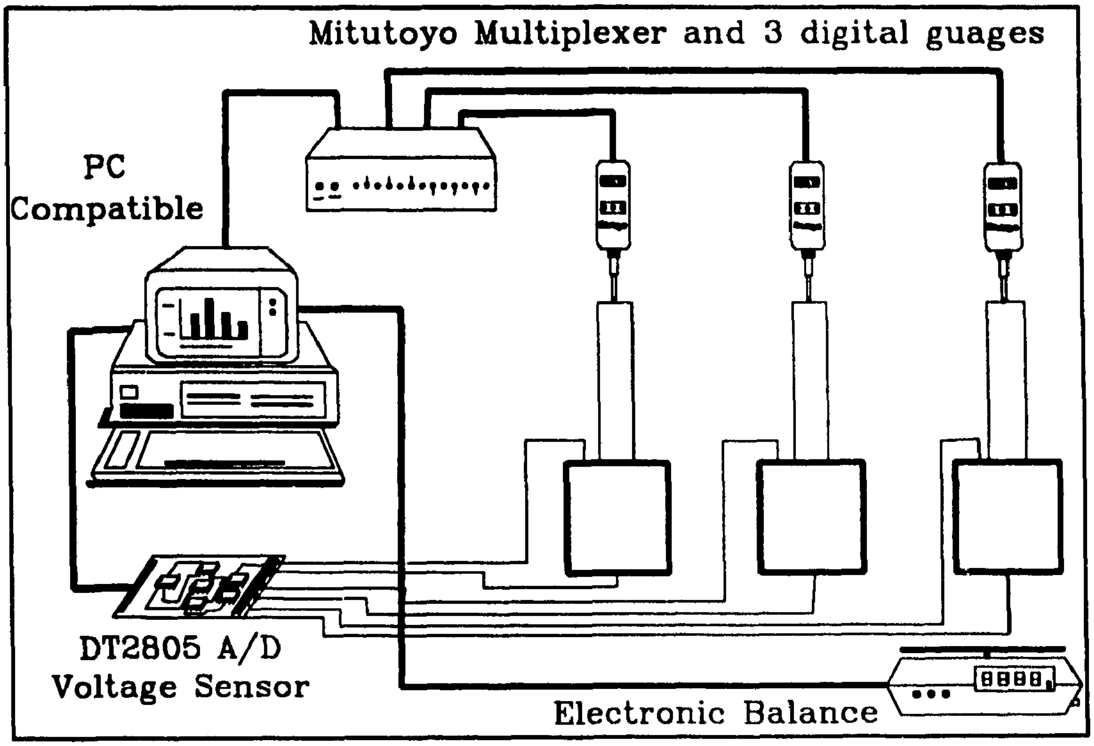

Figure 4.3. Schematic of the instrumentation system for dewatering experiments.

dewatering process (every minute at the beginning of the tests, and about every 5 minutes near the end) and recorded on diskette by an IBM-PC compatible computer. Figure 4.3 shows a schematic of the instrumentation system used for the dewatering experiments.

To calculate electrical energy under constant current, only a voltage measurement was required. An analog to digital interface for the IBM-PC was used to monitor the voltage drop across each dewatering cell. The interface was a DT2805 made by Data Translation.

Mechanical energy was calculated by multiplying the constant load on the dewatering cell by its displacement. Displacement was measured using an IDU25E digital gauge made by Mitutoyo, with a maximum displacement of 26 mm and a resolution of 0.01 mm. The gauges were then monitored by a MIG-1 multiplexer unit made by Mitutoyo, which then transmitted the data to the computer via its RS-232 interface.

A balance to measure the filtrate from one of the three cells was also added to the computer instrumentation through a second RS-232 interface. The balance was an A & D EW-300A, with a maximum load of 300 g and a resolution of 0.1 g.

4.3 Experimental Methods

4.3.1 Sample Collection

All samples were collected from kelp beds near Campbell River, British Columbia during the summer of 1990. Each batch was refrigerated immediately after harvest until it was taken to Comox airport, either the same day or the next morning, for air transport to Dorval. The samples were received the next day, minced in a Moulinex food processor, and refrigerated immediately to 1°C at Macdonald College. All samples were used within 5 days of harvest.

4.3.2 Experimental Designs

The first experiment performed was to determine the effect of the chemical and heat pretreatments described by Hart *et al.* (1978) on the dewatering of *Nereocystis luetkeana*, with and without electro-osmosis. For this experiment, a completely randomized, completely cross classified 4 x 2 design with two replicates was used. The four pretreatments tested were no pretreatment (control), chemical treatment only, heat treatment only, and both chemical and heat treatment. Each of these pretreatments were tested at zero and one Ampere of electric current (219 A/m^2 current density). The pressure used in all of these tests was 104 kPa.

The relative effects of physical pressure and electric current on dewatering of kelp was determined in a second experiment. This experiment was a completely randomized, completely cross classified 4 x 3 design, again with two replicates. Four values of electric current (0, 0.33, 0.67, and 1.00 Ampere) were tested at each of three values of pressure (7.46, 34.6, and 104 kPa). For all of these tests, both chemical and heat treatments preceded dewatering.

4.3.3 Sample Pretreatment

For those samples receiving chemical pretreatment before dewatering, 15 g of 5% calcium chloride were added to 150 g of minced *Nereocystis luetkeana*, resulting in 0.5% $CaCl_2$.

Heat pretreatment consisted of placing the 150 g samples (plus 15 g calcium chloride if chemical pretreatment was also used) in a zip-lock bag and then placing the sealed bag in a hot water bath (77°C) for 30 minutes. Heat treatment was followed by a 5 minute cooling bath (approximately 15°C) before dewatering.

4.3.4 Dewatering

After pretreatment, the samples were put in the dewatering apparatus and allowed to drain for 10 minutes with no pressure or voltage applied. After 10 minutes, mechanical pressure and electric current were applied simultaneously for the following hour. Measurements of voltage, displacement, and mass of filtrate were taken throughout the dewatering process, as described above in section 4.2. The filtrate was collected, and the press cake was removed from the apparatus at the end of the hour for analysis.

4.3.5 Analysis of Press Cake

Dry matter of the press cakes were determined according to ASAE Standard S358.2 for forage material requiring further analysis. Immediately following dewatering, press cakes were weighed and placed in a 60°C oven for 72 hours. The cake was then removed, reweighed, and percent solids of each cake was calculated.

Ash contents of each press cake were determined by placing small weighed samples in a blast furnace at 500°C for 4 hours, removing and reweighing, according to methods of the AOAC (1975). The percent retention of ash in the press cake was then calculated by material balance. Crude protein, fat, available carbohydrate, and uronic acids were also determined for selected treatments according to methods of the AOAC (1975). This complete analysis was done for the untreated seaweed, the 104 kPa and 0 A combination (conventional dewatering), and the 104 kPa and 1.00 Ampere combination (combined fields dewatering).

4.3.6 Analysis of Filtrate

Solids content of the filtrate was determined in the same manner as for the press cake. Percent solids of the raw kelp, the press cakes, and the filtrates were used to calculate a material (water and solids) balance for each experimental unit.

The pH of the filtrate was measured using a digital pH meter immediately following dewatering.

4.4 Roller Press Design

A continuous press was needed for scale up of the combined fields dewatering process. A prototype screw press was found to be ineffective due to the slippery nature of the kelp. It was therefore decided that a roller press would be used for scale up of the combined fields dewatering process.

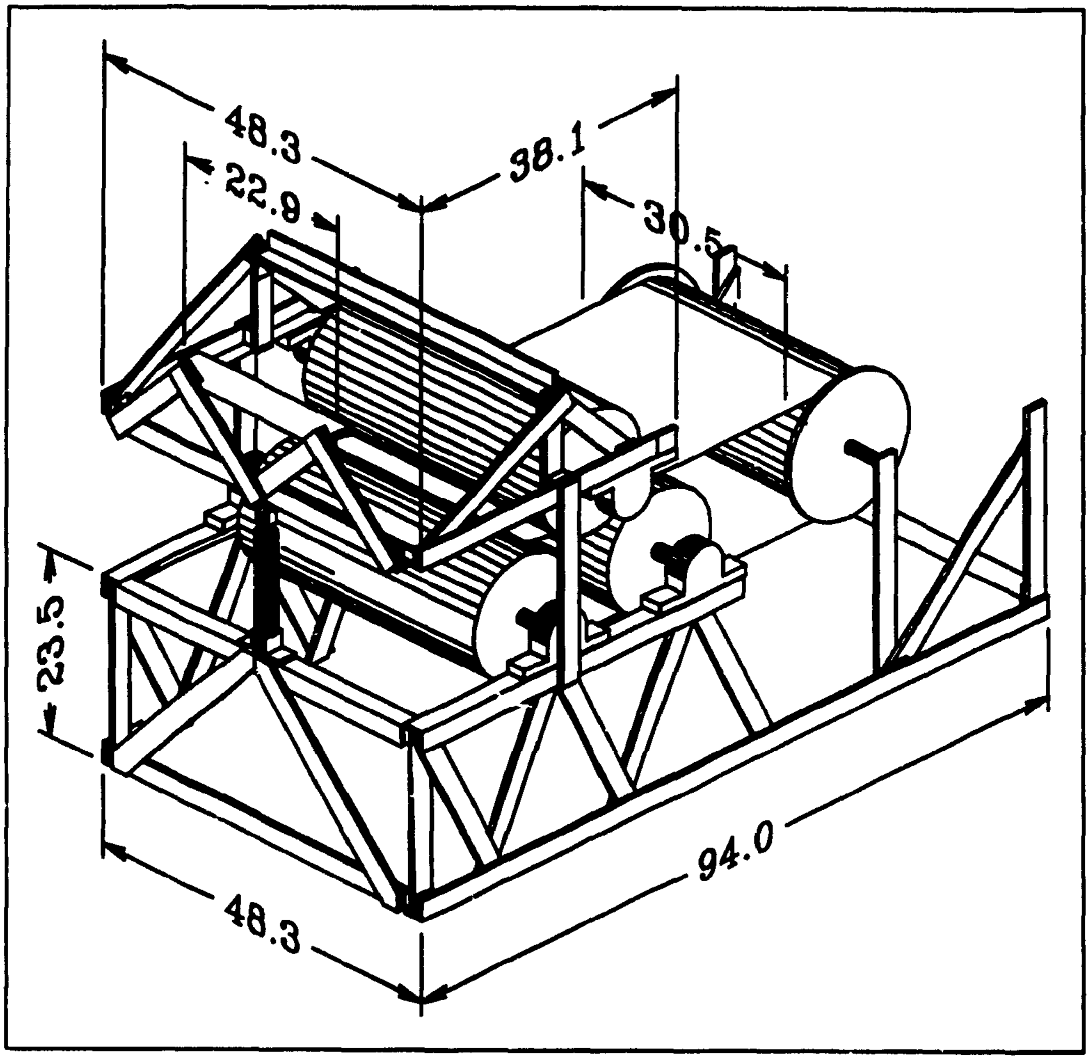

Figure 4.4. Isometric drawing of prototype roller press used for combined fields dewatering of kelp. All measurements are in cm.

Figure 4.4 is an isometric drawing of the prototype roller press. The truss frame was made from structural aluminum (25.4 mm x 6.35 mm rectangular cross section and 25.4 mm x 25.4 mm x 4.76 mm angle) and consisted of a rigid bottom section on which 2 of the press rollers were mounted, and a pivoting top section on which a third press roller was mounted. A hydraulic cylinder was used to pivot the top frame section, which acts as a lever with a mechanical advantage of two, and presses the top roller down onto the two lower rollers. A 304 mm wide fabric belt is stretched around the two bottom press rollers and another roller which is used to provide a loading area for material and maintains belt tension. Overall dimensions of the press are 0.94 m long, 0.51 m wide, and 0.58 m high.

The press rollers were made from 356 mm long sections of 152 mm diameter hollow carbon cylinders with a wall thickness of 19 mm. Inside the carbon cylinders were then fit lengths of 101 mm diameter ABS plastic pipe to provide tensile strength and electrical insulation. The rollers were then mounted on 16 mm shafts with PVC plastic hubs. The shafts were then mounted on NAS P202 pillow block ball bearings on the press frame. The bottom rollers were provided with drains by drilling 228 holes approximately 6 mm in diameter in each roller.

The fourth roller was pivoted from the bottom of the frame and was attached by two springs to the frame at the feed loading end to provide belt tension. This roller was made from 305 mm of 152 mm diameter PVC plastic pipe and was mounted on a 12.7 mm diameter shaft with PVC plastic hubs and sealed ball bearings.

Force was applied to the top roller by way of a 22.2 mm bore hydraulic cylinder. The force from this cylinder was then increased by the lever action of the top portion of the aluminum frame.

Electricity was applied between the top roller and the two bottom rollers by way of pivoted spring loaded carbon brushes. The carbon brushes were mounted on plexiglass to prevent shorting through the press frame. A 12 V automotive battery and charger were then connected in parallel to the press to provide continuous voltage for electro-osmosis. Foam produced between the top roller and the first bottom roller was found to prevent proper feeding of material, so electricity was applied between the top roller and the second bottom roller only.

Plexiglass scrapers were made and mounted on the press. The bottom scraper was found to be ineffective at cleaning the belt, so it was later replaced by a revolving brush.

A sheet of polyethylene plastic was draped beneath the press to catch the filtrate as it fell from the belt and rollers above.

4.5 Evaluation of Continuous Process

The kelp used for the continuous process trials was harvested during summer 1991 from kelp beds south of Campbell River, B. C. The kelp was then taken directly to the pilot dewatering operation in Courtenay, 25 km south-east. The kelp was ground in a hammer mill type shredder with a screen size of 18 mm. Chemical pretreatment with aqueous $CaCl_2$, as described previously for the lab tests, was then applied to the kelp, followed by either heat pretreatment or a twelve hour rest. Heat pretreatment, as described for the lab tests, was performed on most of the kelp before dewatering. For a few of the later runs, the heat pretreatment was replaced by a rest period of about twelve hours after addition of the $CaCl_2$. The effect of this pretreatment on dewatering was then noted.

Different continuous dewatering processes were tested with the roller press described above. Processes involving single and multiple pass pressing, different values of pressure, and with or without electro-osmosis were tested. These different processes were evaluated on a press cake percent solids basis only. From these results, it was concluded that the best continuous process would be a double pass operation, with electro-osmosis used only on the second pass, with a total downward force of 1620 N on the top roller, and with a belt speed of 0.0047 m/s. Further analysis was done on the press cake from this process.

The press cake was analyzed for total ash, crude protein, crude fat, total available carbohydrates, and total uronic acid. These tests were performed according to methods of the AOAC (1975).

V. RESULTS AND DISCUSSION

5.1 Pretreatment Effects

For the pretreatment experiment, press cake percent solids were calculated for each experimental unit. The results of these calculations are given in Table 5.1, and shown graphically in Figure 5.1. A statistical analysis of these data found the effects of pretreatment and electric current on press cake percent solids to be highly significant ($\alpha = 0.01$). Both heat and chemical pretreatment were significantly different from no pretreatment, but not significantly different from each other. Combining chemical and heat

Table 5.1. Press cake percent solids from pretreatment experiment.

	Pretreatment before dewatering			
Current (A)	none (% solids)	heat (% solids)	$CaCl_2$ (% solids)	$CaCl_2$ + heat (% solids)
0.00	9.4	10.5	10.9	13.5
0.00	9.9	10.5	11.3	12.8
1.00	11.1	12.8	12.7	15.0
1.00	11.5	13.4	13.1	15.3

Solids of fresh kelp: 9.10%
Solids of kelp + $CaCl_2$ slurry: 8.73%

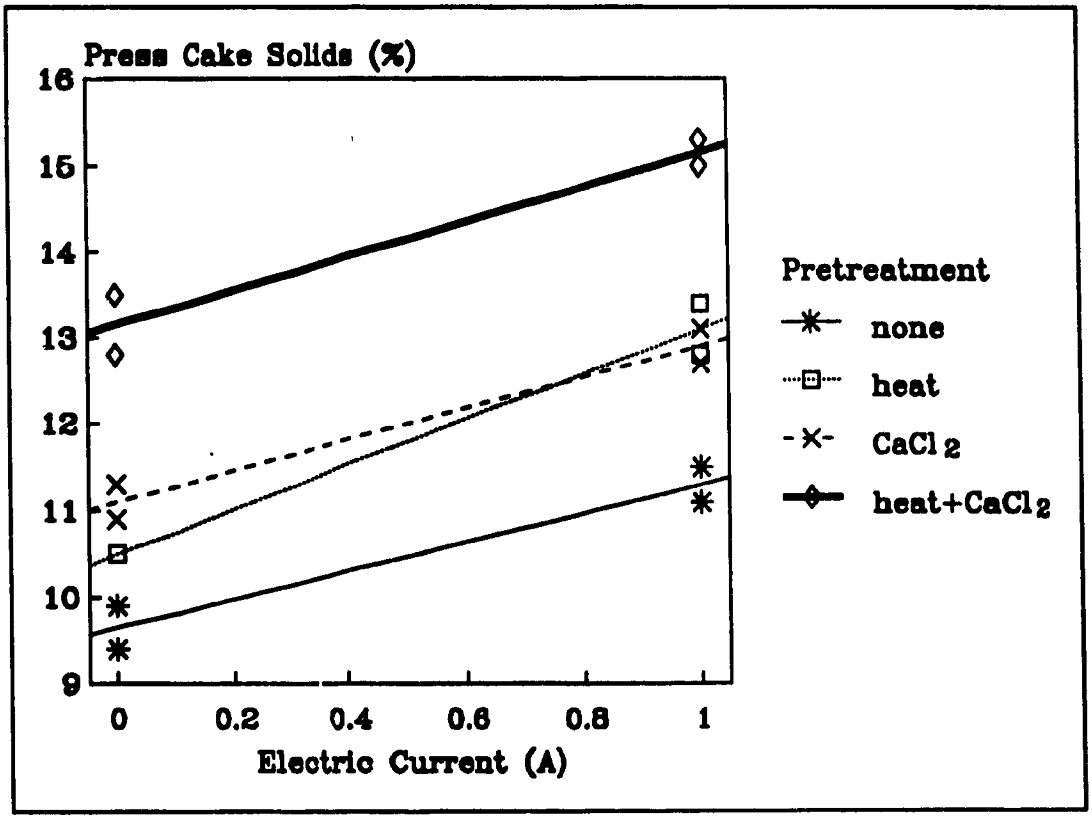

Figure 5.1. Percent solids of press cake as a function of electric current for different pretreatments.

pretreatments resulted in press cake percent solids significantly higher than either pretreatment applied alone. Complete results of the statistical analysis are given in Appendix A.

During this first experiment it was also observed that the electro-osmosis caused discolouration of the press cake at the anode, giving it a yellow-brown appearance instead of the dark green colour of the rest of the press cake. The electro-osmosis was also found to produce a small amount of chlorine gas from the electrolysis of the press cake juice.

5.2 Pressure and Electrical Current Effects

5.2.1 Material Balances

For the main pressure-current experiment, percent solids of both press cake and filtrate were calculated for each experimental unit. The percent solids were then used for a material balance to determine how much of the original mass, solids and water remained in the press cake. Details of the material balance calculations are given in Appendix C. The percent solids and results of the material balance calculations are given in Table 5.2. Percent solids of the press cake is graphed as a function of electric current for each applied pressure in Figure 5.2. Figure 5.3 shows the mass remaining in the press cake as a function of electric current for each pressure, and Figures 5.4 and 5.5 show the mass of water and solids respectively remaining in the press cake as a function of electric current for each applied pressure.

Statistical analysis found the effects of both pressure and electric current on press cake percent solids to be significant ($\alpha = 0.01$), with a significant interaction effect as well. Neither pressure nor electric current were found to have a significant effect on filtrate percent solids ($\alpha = 0.05$).

The mass of water remaining in the press cake, the mass of solids remaining in the press cake, and the total mass of the press cake were all significantly affected by pressure and by electrical current ($\alpha = 0.01$), with no significant interaction effect (α=0.05).

Table 5.2. **Results of material balances for pressure-current combinations.**

Current (Amps)	Press. (kPa)	Cake Solids (%)	Filtrate Solids (%)	Total Mass in Cake (g)	Mass of Solids in Cake (g)	Mass of Water in Cake (g)
0.00	7.46	11.9%	5.9%	79.50	9.46	70.04
0.00	7.46	12.5%	5.8%	73.66	9.21	64.45
0.00	34.6	13.0%	5.6%	71.15	9.25	61.90
0.00	34.6	13.6%	5.7%	64.56	8.75	55.78
0.00	104.0	13.0%	5.6%	71.15	9.25	61.90
0.00	104.0	13.0%	5.6%	71.15	9.25	61.90
0.33	7.46	12.0%	5.4%	84.77	10.17	74.60
0.33	7.46	12.4%	5.7%	76.12	9.44	66.68
0.33	34.6	13.1%	5.3%	73.85	9.67	64.17
0.33	34.6	13.3%	5.4%	70.82	9.42	61.40
0.33	104.0	13.7%	5.3%	68.57	9.39	59.18
0.33	104.0	14.1%	5.5%	63.14	8.90	54.24
0.67	7.46	12.6%	5.6%	75.21	9.48	65.74
0.67	7.46	13.1%	5.5%	71.45	9.36	62.09
0.67	34.6	13.4%	5.6%	67.50	9.04	58.45
0.67	34.6	13.4%	5.5%	68.73	9.21	59.52
0.67	104.0	15.0%	5.5%	57.16	8.57	48.58
0.67	104.0	15.7%	5.4%	54.32	8.53	45.79
1.00	7.46	13.3%	5.5%	69.62	9.26	60.36
1.00	7.46	12.1%	5.7%	79.69	9.64	70.05
1.00	34.6	14.7%	5.5%	59.02	8.68	50.35
1.00	34.6	15.8%	5.8%	49.35	7.80	41.55
1.00	104.0	16.1%	5.7%	49.04	7.90	41.14
1.00	104.0	16.1%	5.2%	54.36	8.75	45.61

Starting material:

150 g of fresh kelp (9.17% solids)
15 g of 5% $CaCl_2$ solution (5% solids)

150.50 g of water
14.50 g of solids

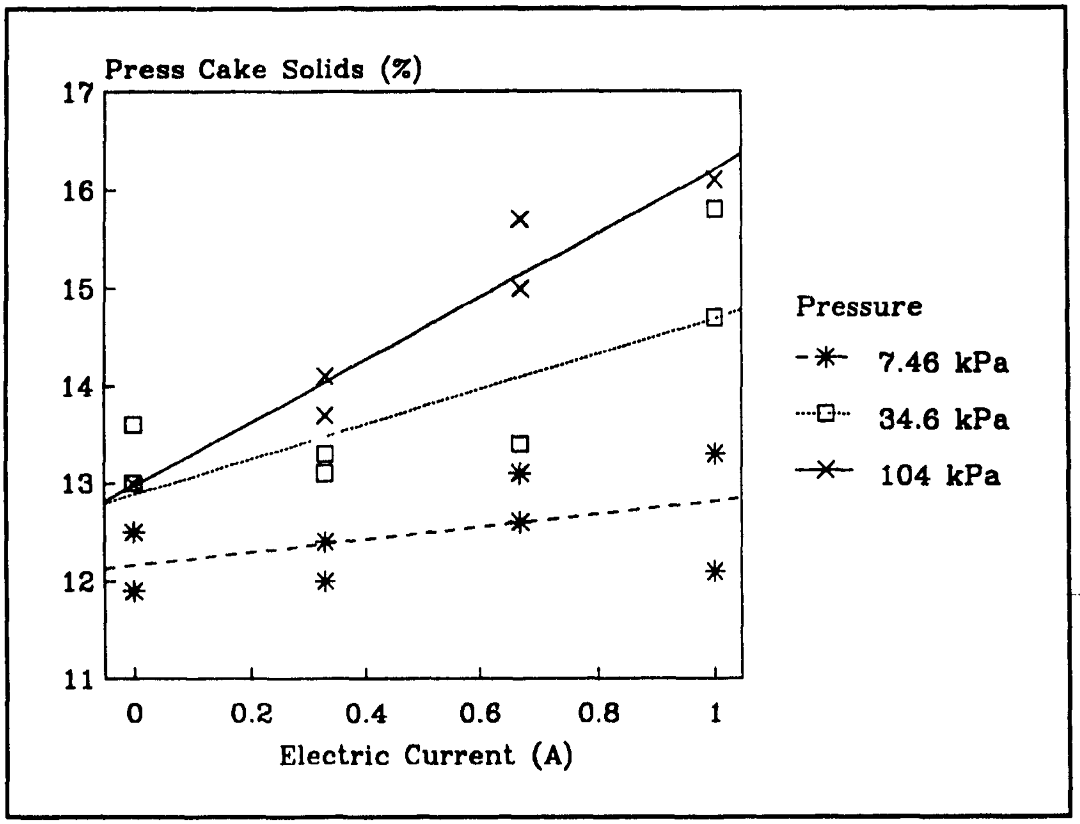

Figure 5.2. Percent solids of press cake as a function of electric current at three different pressures.

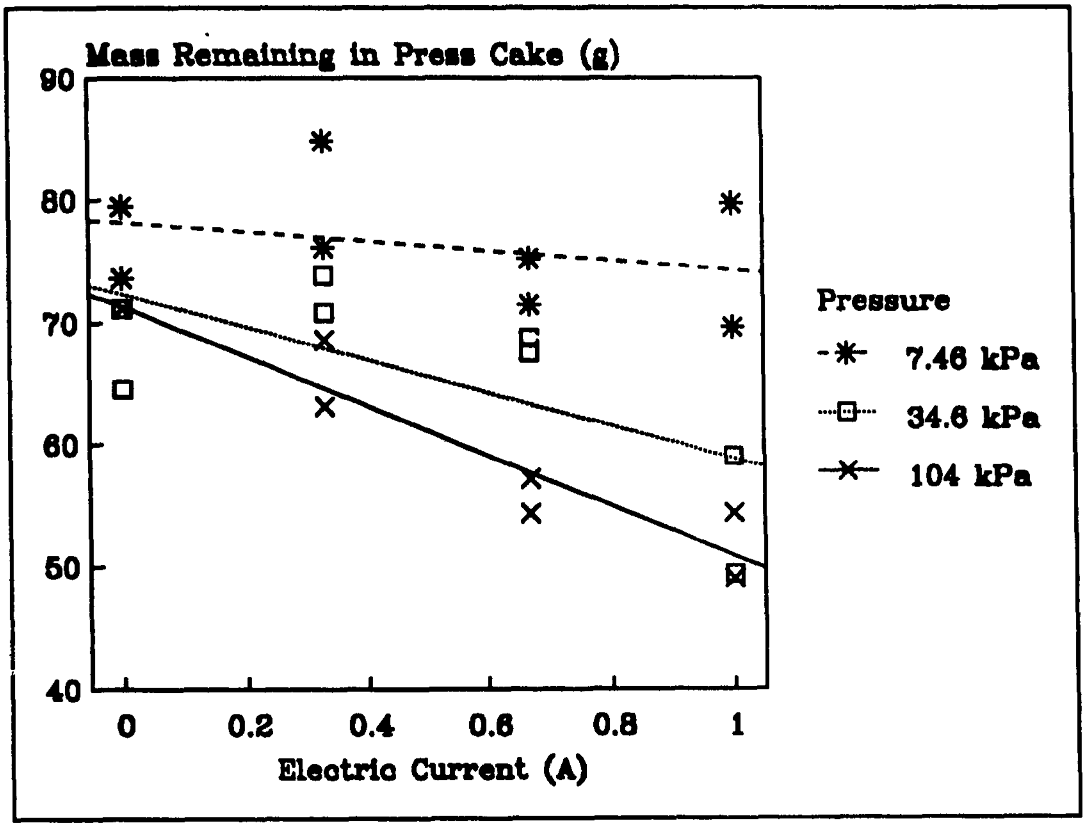

Figure 5.3. Mass remaining in press cake as a function of electric current at three different pressures.

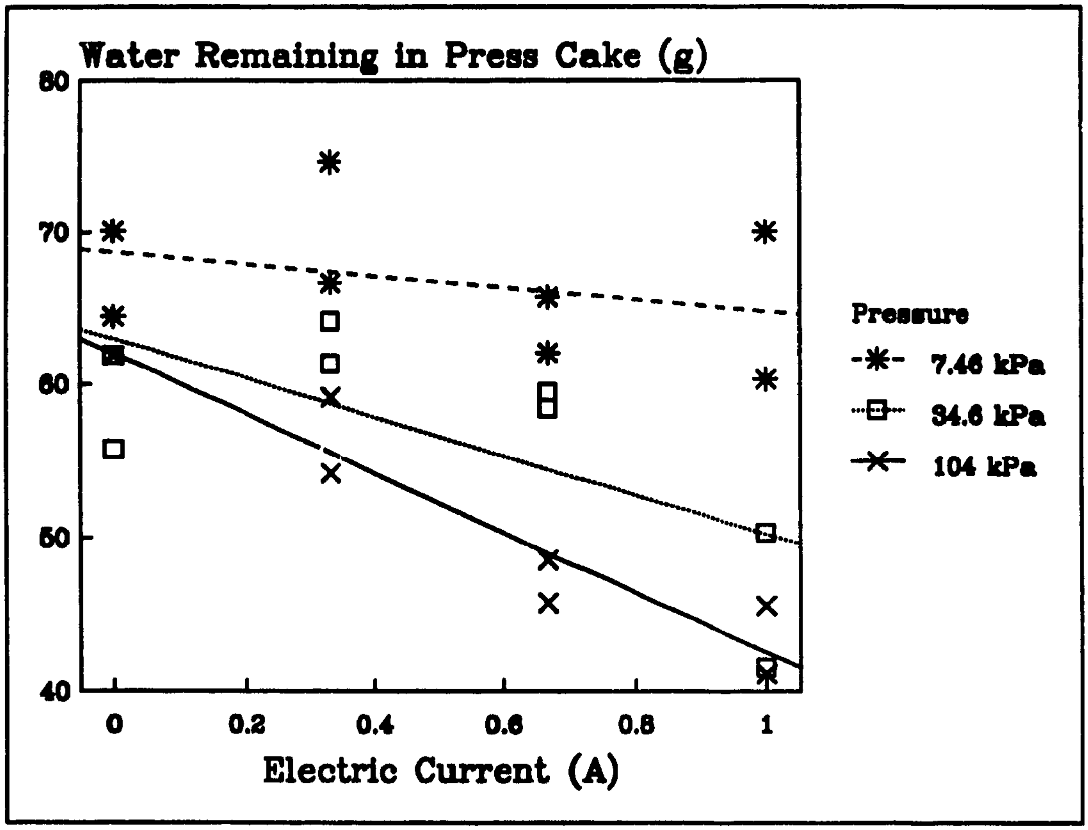

Figure 5.4. Mass of water remaining in press cake as a function of electric current at three different pressures.

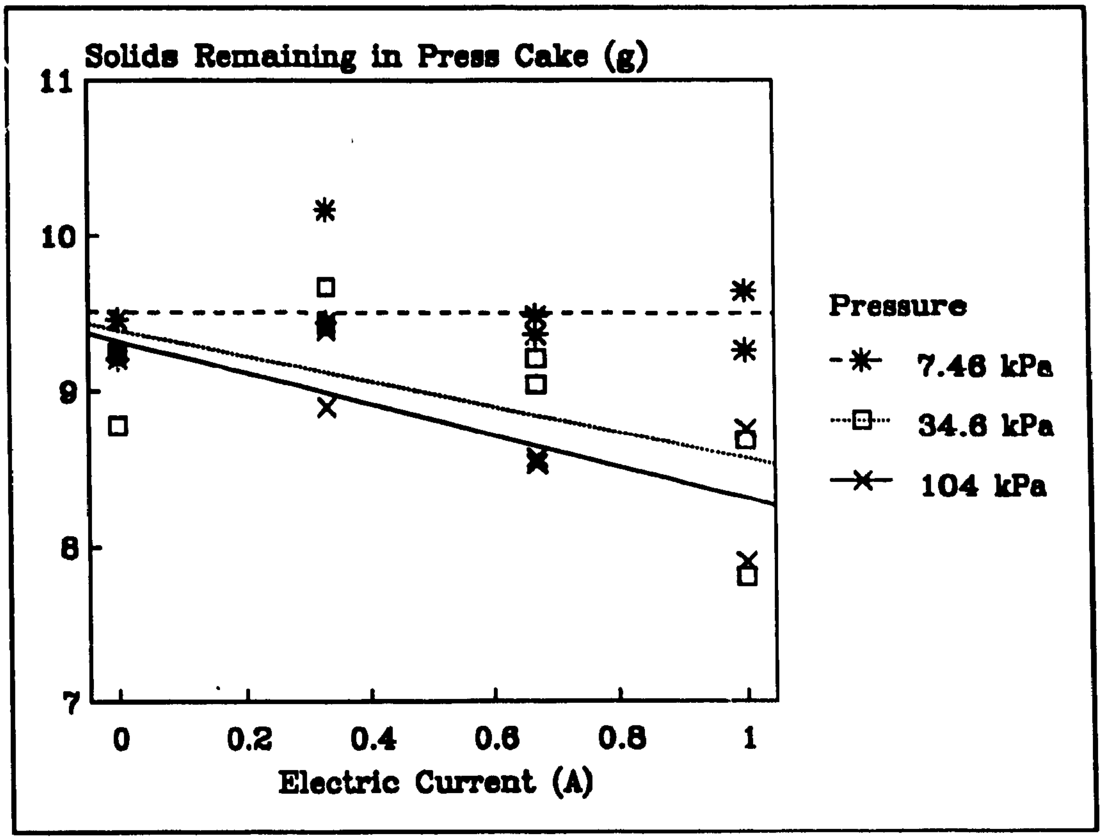

Figure 5.5. Mass of solids remaining in press cake as a function of electric current at three different pressures.

The total mass remaining in the press cake and the mass of water remaining in the press cake were modeled as functions of pressure and electric current. These two parameters were modeled because they were significantly affected by pressure and electric current with no interaction effect, and all other parameters in the material balance can be calculated knowing these two and the the original percent solids of the kelp and calcium chloride solution mixture.

The total mass remaining in the press cake and the mass of water remaining in the press cake were both fit to a linear model and a linear-log model, in which the parameters were related to the natural logarithm of pressure. The data were fit to the models using the GLM (general linear model) procedure of SAS on an IBM-PC, and Appendix B gives the complete results and statistical analysis of the models fit. In both cases, the linear-log model was found to fit the data better than the linear model, and they are shown below:

$$m_{cake} = 93.78 - 12.65\, I - 5.821 \ln P \tag{1}$$

$$m_{water} = 83.47 - 12.03\, I - 5.557 \ln P \tag{2}$$

where m_{cake} is the total mass remaining in the press cake in grams, m_{water} is the mass of water remaining in the press cake in grams, I is the electrical current in amperes, and P is the pressure applied in kPa. Given the original percent solids of the material, s_o, one can now calculate values for the rest of the material balance parameters:

$$m_{solids} = m_{cake} - m_{water} \tag{3}$$

$$s_{cake} = \frac{m_{cake} - m_{water}}{m_{cake}} \tag{4}$$

$$s_{filtrate} = \frac{165\, s_o - m_{solids}}{165 - m_{cake}} \tag{5}$$

where m_{solids} is the mass of solids in the press cake in grams, s_{cake} is the percent solids of the press cake, and $s_{filtrate}$ is the percent solids of the filtrate.

According to the literature (Lockart and Hart, 1986; Yoshida and Yukawa, 1988, 1986), increasing the electric current should effect a linear increase in the rate of water removal, and therefore in the total amount of water removed. This linear relationship between electric current and water removal should continue until drying occurs at one of the electrodes, which would increase the electrical resistance of the press cake significantly. Since nearly constant voltage drop (and therefore resistance) was observed during dewatering with one Ampere of electric current, this was obviously not close to the maximum electrical current possible. Higher current densities would likely have shown a linearly increasing rate of water removal, making faster and more complete dewatering possible. Unfortunately, equipment limitations prevented the study of higher electrical currents.

5.2.2 Press Cake Composition

The ash content and percent retention of ash in press cakes from all experimental units in the main experiment were determined and are given in Table 5.3. All ash contents were significantly lower than the ash content of the untreated kelp (39.4%). Although there was no significant effect of electric current or applied pressure on press cake ash content ($\alpha = 0.05$), both current ($\alpha = 0.01$) and pressure ($\alpha = 0.05$) had a significant effect on the retention of

Table 5.2. Press Cake ash content and ash retention for pressure-current combinations.

Current (Amps)	Press. (kPa)	Cake Ash (%)	Ash Retained in Cake (%)
0.00	7.46	35.5	55.9
0.00	7.46	25.7	40.3
0.00	34.6	33.5	54.2
0.00	34.6	31.7	48.0
0.00	104.0	33.0	53.5
0.00	104.0	30.4	49.2
0.33	7.46	32.8	60.1
0.33	7.46	34.0	55.4
0.33	34.6	33.0	58.2
0.33	34.6	33.2	56.1
0.33	104.0	29.5	50.3
0.33	104.0	30.3	47.8
0.67	7.46	31.9	52.8
0.67	7.46	32.0	53.2
0.67	34.6	31.5	49.9
0.67	34.6	29.5	48.1
0.67	104.0	28.1	42.6
0.67	104.0	21.6	32.9
1.00	7.46	30.4	49.9
1.00	7.46	30.9	51.4
1.00	34.6	26.9	41.3
1.00	34.6	25.9	34.7
1.00	104.0	29.8	40.7
1.00	104.0	27.4	43.5

ash in the press cake. In general, it can be seen that the lower ash content and lower ash retention values correspond to the treatments which gave the greatest dewatering.

Table 5.4. Proximate composition of untreated kelp, conventionally dewatered kelp, and combined field dewatered kelp.

Treatment	Ash	Crude Fat	Crude Protein	Available Carbo.	Uronic Acid
None	39.39a	1.96a	13.58a	1.87a	8.54a
Pressure Only	31.70b	2.70a	15.26a	0.79b	11.29a
Combined Fields	28.59b	2.88a	15.35a	0.97b	10.28a

All data presented as percent of total dry matter by weight. Data given are means of two samples. Means with the same letter are not significantly different.

Table 5.4 gives the major constituents in the conventionally dewatered press cakes (104 kPa pressure only) and the combined fields press cakes (104 kPa and 1 Ampere electric current) and compares them with the composition of the untreated kelp. Ash, crude fat, crude protein, available carbohydrates, and total uronic acid were determined for each sample.

Ash contents in the press cakes were significantly lower than in the untreated kelp ($\alpha = 0.05$), but there was no significant difference between the two dewatering methods. The lower ash contents in the press cakes are the result of leaching of some of the soluble salts with the filtrate.

Crude fat, crude protein, and uronic acid contents were all higher in the press cakes than in the untreated kelp, but no significant difference was observed (α = 0.05). The higher contents in the press cakes are due to the insoluble nature of fat, protein, and uronic acid which causes concentration in the press cake from dewatering.

Available carbohydrates were significantly higher in the untreated kelp than in the press cakes (α = 0.01), while no significant difference was observed between the two dewatering methods (α=0.05). The lower available carbohydrate content in the press cakes is likely due to a loss of soluble carbohydrates, such as mannitol and fucoidan, with the filtrate.

5.2.3 Filtrate pH

The pH of the filtrate was measured for each experimental unit in the main experiment. The results, showing increasing acidification with increasing electrical current, are shown in Figure 5.6. A statistical analysis showed filtrate pH to be significantly affected by electric current (α = 0.01), while there was no significant effect due to pressure (α = 0.05). The decrease in filtrate pH with increasing electric current supports the assumption that the kelp has a positive zeta potential. This assumption was made after preliminary dewatering trials showed that dewatering was more effective when the bottom electrode acted as the anode.

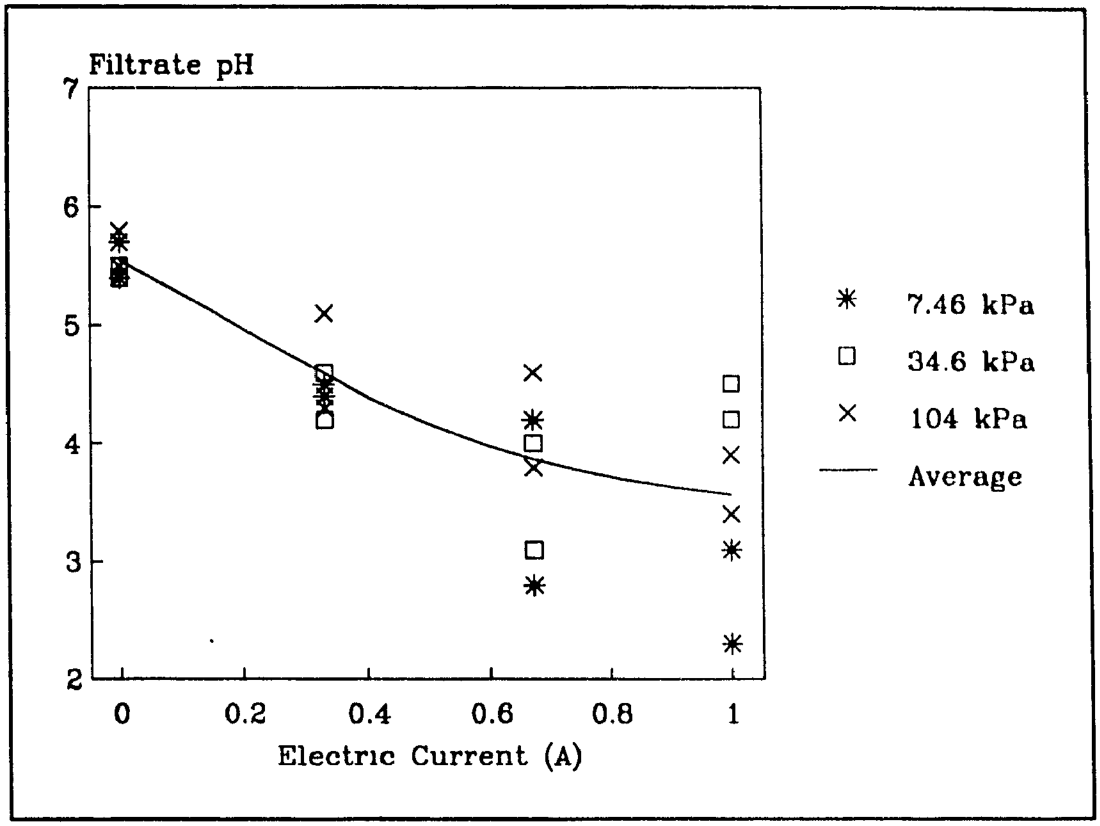

Figure 5.6. Filtrate pH as a function of electric current.

5.2.4 Energy Calculations

Electrical and mechanical energy required for each treatment were calculated from the data collected during dewatering. Table 5.5 shows the electrical and mechanical energy used for each test. The electrical energy was found to be significantly affected by electric current ($\alpha = 0.01$), while pressure had no observed effect (α=0.05). Mechanical energy was found to be significantly affected by pressure (α=0.01), while electric current had no effect (α=0.05).

Table 5.5. Electrical and mechanical energy requirements for different pressure-current combinations.

Current (Amps)	Pressure (kPa)	Electrical Energy (J)	Mechanical Energy (J)
0.00	7.46	0	0.050
0.00	7.46	0	0.057
0.00	34.6	0	0.638
0.00	34.6	0	0.796
0.00	104.0	0	4.962
0.00	104.0	0	4.800
0.33	7.46	4,764	0.064
0.33	7.46	4,714	0.051
0.33	34.6	4,484	0.753
0.33	34.6	4,615	0.660
0.33	104.0	5,048	4.045
0.33	104.0	4,045	6.030
0.67	7.46	11,115	0.084
0.67	7.46	10,419	0.083
0.67	34.6	9,942	0.875
0.67	34.6	10,103	1.146
0.67	104.0	9,242	3.721
0.67	104.0	9,369	3.877
1.00	7.46	15,606	0.110
1.00	7.46	16,592	0.064
1.00	34.6	16,255	1.076
1.00	34.6	15,498	0.996
1.00	104.0	14,189	6.848
1.00	104.0	16,244	4.730

Although the electrical energy input was several orders of magnitude higher than the mechanical energy input, the total energy required to remove 1 kg of water (144 kJ for 1.00 Amp and 104 kPa) is still an order of magnitude less than the total energy to evaporate 1 kg of water (approximately 2250 kJ

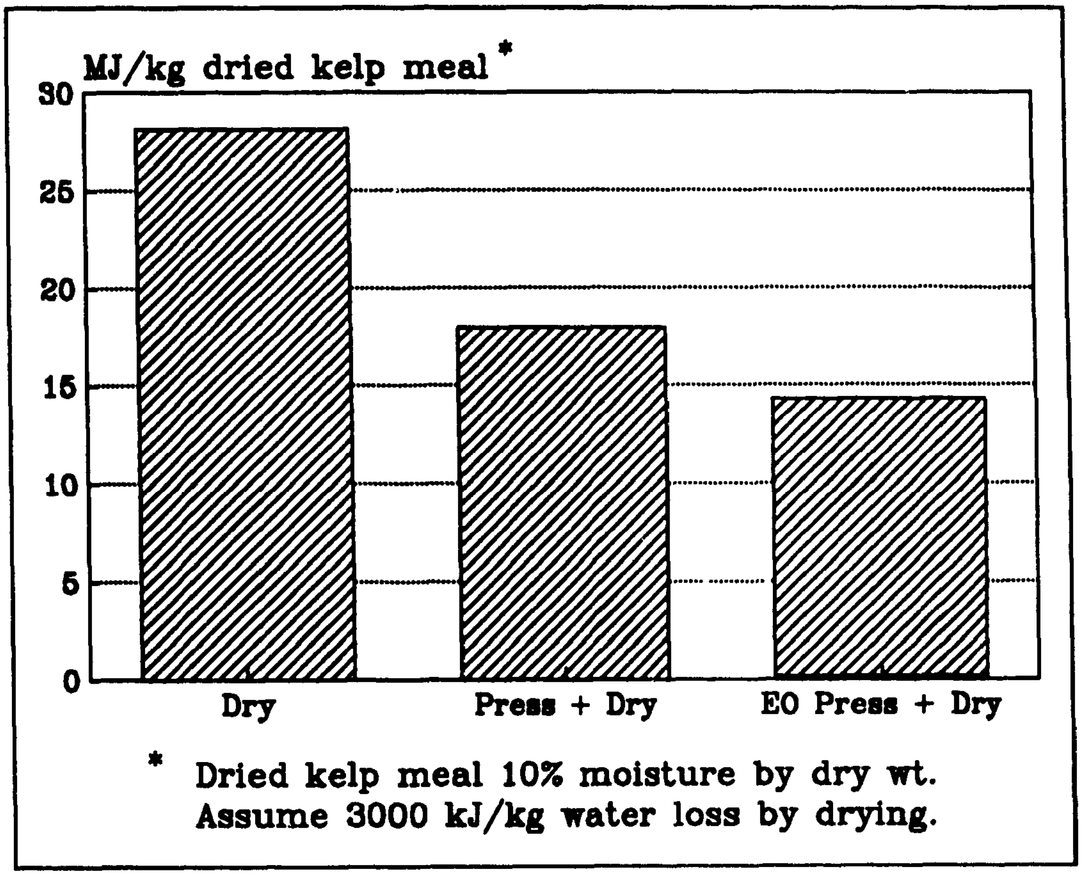

Figure 5.7. Total energy requirements for producing kelp meal by drying, by press dewatering followed by drying, and by combined fields dewatering followed by drying.

at 100°C, assuming 100% efficiency). By removing up to 71% of the water by dewatering, we can expect significant energy savings in dried kelp meal production. Figure 5.7 shows the energy requirements for producing dried kelp meal (10% moisture by dry weight) by drying alone, by conventional press dewatering followed by drying, and by combined field electro-osmosis and press dewatering followed by drying. As can be seen from the figure, dewatering energy constitutes a very minor percent of the total energy requirement, even for combined fields dewatering.

Increasing the electric current above one Ampere would have increased the dewatering energy requirement, but the reduced water in the press cake would reduce drying costs and likely total energy costs would be less. Further study with higher electric currents will be required to determine the optimal dewatering-drying combination for the most efficient use of energy.

5.3 Continuous Process

The roller press described in section 4.4 of this thesis was used to dewater kelp during the summer of 1991. Different values of pressure, voltage, belt speeds, and more than one pass through the press were tested for dewatering kelp. Table 5.6 gives the percent solids of the press cake from the roller press under different operating conditions. In all treatments with two passes through the press, voltage was applied across the material on the second pass only. This was found to reduce the amount of foam produced, allowing better feeding of the material, and also reduced the discolouration of the press cake material due to oxidation. The result from the two passes was a dark green flaky material.

As can be seen from Table 5.6, the press cake percent solids was increased by increasing the pressure (force on top roller), by including electro-osmosis, and by increasing the number of passes through the press. Increasing

Table 5.6. Press cake percent solids from roller press under different operating conditions.

Force On Top Roller (N)	Voltage (V)	Belt Speed (m/s)	# Passes	Press Cake % Solids
540	12	7.85×10^{-4}	1	13.85
1620	0	7.85×10^{-4}	1	16.45
1620	12	7.85×10^{-4}	1	21.75
1620	12	7.85×10^{-4}	2	33.65
1620	12	4.71×10^{-3}	2	20.90
1620	12	4.71×10^{-3}	2	19.75*

*Heat pre-treatment replaced by a 12 hour rest period after $CaCl_2$ added.

the belt speed had a negative effect on press cake percent solids, but it was found to be necessary to improve the capacity of the press. Replacing the heat pretreatment with a twelve hour rest period after the addition of calcium chloride was found to result in slightly lower percent solids in the press cake, but this difference is likely not worth the energy cost to heat the material.

The application of 12 Volts of electric potential resulted in between 7 and 12 Amperes of electric current through the press rollers and the press cake. The electric potential caused a sizzling sound between the rollers, and produced a faint chlorine smell around the press.

Chemical analysis was done on the press cake produced with two passes, 1620 N on the top roller, 12 Volts of electric potential during the second pass only, and a belt speed of 4.71×10^{-3} m/s. The composition of the press cake and fresh untreated kelp harvested at the same time are given in Table 5.7.

Table 5.7. Proximate composition of untreated kelp and dewatered kelp from combined fields roller press.

Treatment	Ash	Crude Fat	Crude Protein	Available Carbo.	Uronic Acid
Untreated	42.25a	1.72a	13.40a	2.24a	11.60a
Dewatered	30.02b	1.89a	16.48b	1.58a	11.02a

All data presented as percent of total dry matter by weight. Data given are the mean of three samples. Means with the same letter are not significantly different.

Statistical analysis of the chemical analysis showed that ash content was significantly lowered by dewatering ($\alpha = 0.01$), due to the loss of soluble salts, such as chlorides of potassium and sodium, in the filtrate. Protein was found to be significantly higher ($\alpha = 0.01$) in the press cake than in the untreated kelp. This was likely due to a concentrating effect due to high retention of protein in the press cake. There was no significant effect ($\alpha = 0.05$) from dewatering on the crude fat, available carbohydrate, or uronic acid contents of the kelp.

The electrical power used for electro-osmosis varied between 80 and 150 Watts (between about 7 and 12 Amps and 12 Volts d.c.). The power used to turn the press rollers and move the belt at 4.17×10^{-3} m/s was approximately 120 Watts (120 Volts a.c. electric motor at 1 Ampere). The total energy requirement for the press was then approximately 250 Watts. Given that the processing rate of the roller press under these conditions was about 1.5 kg/hr and the press cake was about 21% solids, the energy required to produce 1 kg of kelp meal (10% moisture by dry weight) would be 2600 kJ for dewatering and 10,000 kJ for drying, for a total of 12,600 kJ/kg of kelp meal produced. This value compares well with approximately 24,300 kJ/kg to produce kelp meal by drying alone (assuming 3000 kJ/kg of water removed by drying).

The prototype roller press was found to be too small (processing only 1.5 kg of material per hour) and required too much labour (re-feeding the material through the press) for practical use. A larger version of the combined fields press should have more rollers so that the material only needs to be fed through the machine once. Larger diameter rollers may lessen the slippage of material, allowing a thicker layer to be processed. Increased belt width and belt speed will also increase the capacity of the press. If the belt speed is increased, however, a sufficient number of rollers would be required to ensure an adequate residence time of the material in the press.

VI. CONCLUSIONS

Electro-osmosis has been shown to significantly improve conventional press dewatering of kelp. The effects of combining pressure with electro-osmosis were determined. The amount of water removed by dewatering was found to increase linearly with electric current density up to 219 A/m^2 and logarithmically with pressure up to 104 kPa. The effect of more intense electrical and pressure fields were not determined.

Dewatering kelp, with or without electro-osmosis, was found to significantly reduce ash contents and available carbohydrates due to leeching of these materials with the filtrate. Protein, fat, and uronic acid contents were found to be slightly higher in the dewatered kelp due to high retention of these materials in the press cake, although the difference was found to be statistically insignificant.

Energy costs for producing dried kelp meal were found to be significantly lower if dewatering precedes thermal drying. The electro-osmosis was also found to result in significant total energy savings over conventional dewatering if dewatering is followed by drying to produce the finished product.

The combination of electro-osmosis and pressure was then successfully scaled up to a continuous process with a prototype roller press. The press was found to be able to produce a press cake with up to 33.5% solids. The press produced a press cake with 20.90% solids at a more reasonable operating speed, the resulting press cake being significantly lower in ash and significantly higher in protein than untreated kelp. The kelp meal produced by this press required about half the energy used to produce conventional dried kelp meal feed by drying alone.

The potassium and trace minerals in the kelp filtrate are also of potential agricultural value. The phyto-hormonal activity of the filtrate may be of greater value, but the activity has not yet been determined.

VII. REFERENCES

AOAC. 1975. Official methods of analysis, 12th ed. Association of Official Agricultural Chemists, Washington, D.C.

ASAE. 1989. Standards. American Society of Agricultural Engineers, St. Joseph, Michigan.

Barta, E. S., A. L. Branen, and H. K. Leung. 1981. Nutritional analysis of Puget Sound bull kelp (*Nereocystis luetkeana*). Journal of Food Science 46(2) 494-497.

Beames, R. M., R. M. Tait, J. N. C. Whyte, and J. R. Englar. 1977. Nutrient utilization experiments with growing pigs fed diets containing from 0 to 20% kelp (*Nereocystis luetkeana*) meal. Canadian Journal of Animal Science 57: 121-129.

Beleau, M. H., N. D. Heidelbaugh, and D. Van Dyke. 1975. Open-ocean farming of kelp for conversion to animal and human foods. Food Technology 29(12): 27-30, 45.

Black, W. A. P. 1955. Seaweeds and their constituents in foods for man and animal. Chemistry and Industry, December 17, 1955: 1640-1645.

Blunden, G. 1971. The effects of aqueous seaweed extracts as a fertilizer additive. Proceedings of the 7th International Seaweed Symposium, Sopporo, Japan, August 8-12, 1971: 584-589.

Blunden, G. and P. B. Wildgoose. 1977. The effects of aqueous seaweed extract and kinetin on potato yields. Journal of the Science of Food and Agriculture 28: 121-125.

Blunden, G., P. B. Wildgoose, and F. E. Nicholson. 1974. The effects of aqueous seaweed extract on sugar beet. Proceedings of the 8th International Seaweed Symposium, Bangor, North Wales, August 18-23, 1974: 667-672.

Booth, E. 1965. Some properties of seaweed manures. Proceedings of the 5th International Seaweed Symposium, Halifax, Nova Scotia, August 25-28, 1965: 349-357.

Booth, E. 1968. The manufacture and properties of liquid seaweed extracts. Proceedings of the 6th International Seaweed Symposium, Santiago de Compostela, September 9-13, 1968: 655-662.

Brain, K. R., M. C. Chalopin, T. D. Turner, G. Blunden, and P. B. Wildgoose. 1973. Cytokinin activity of commercial aqueous seaweed extract. Plant Science Letters 1: 241-245.

Chauhan, S. P., B. C. Kim, H. S. Muralidhara, N. Senapati, B. Jirjis, and C. L. Criner. 1989. Scale-up of electroacoustic dewatering (EAD) process for food products. Presented at the 1989 summer national AIChE meeting, Philadelphia, Pennsylvania. 30 pp.

Desai, M. C. and P. C. Shukla. 1975. Effect of feeding seaweed to lactating cows on body weights and milk production. Indian Journal of Animal Science 45(11): 823-827.

Ensminger, D. 1988. Acoustic and electroacoustic methods of dewatering and drying. Drying Technology 6(3): 473-499.

Featonby-Smith, B. C. and J. Van Staden. 1983. The effect of seaweed concentrate on the growth of tomato plants in nematode infested soil. Scientia Horticulturae 20: 137-146.

Foreman, R. E. 1983. Studies on *Nereocystis* growth in British Columbia, Canada. Proceedings of the 11th International Seaweed Symposium, Qingdao, China, June 19-25, 1983: 325-332.

Hart, M. R., D. de Fremery, C. K. Lyon, and G. O. Kohler. 1977. Processing *Macrocystis pyrifera* (Phaeophyceae) for fermentation to methane. Proceedings of the 9th International Seaweed Symposium, Santa Barbara, California, August 20-27, 1977: 493-498.

Hart, M. R., D. de Fremery, C. K. Lyon, and G. O. Kohler. 1978. Dewatering kelp for fuel, feed, and food uses: Process description and material balances. Transactions of the ASAE 21(1): 186-190, 196.

Hart, M. R. and G. O. Kohler. 1986. Effect of particle size on desalting and bioconversion of kelp to methane. Transactions of the ASAE 29(2): 611-615.

Herbert, J. G., G. Weiner, and A. C. Field. 1978. The effect of breed and of dried seaweed meal in the diet on levels of copper in liver, kidney and plasma of sheep fed on a high copper diet. Animal Production 26: 193-201.

Jayal, M. M., V. K. Jain, and S. K. Ranjhan. 1978. A note on seaweed residue as a calcium and trace mineral source in rations of growing calves. Indian Journal of Animal Science 48(2): 147.

Jensen, A. 1971. The nutritive value of seaweed meal for domestic animals. Proceedings of the 7th International Seaweed Symposium, Sapporo, Japan, August 8-12, 1971: 7-14.

Jensen, A. 1977. Industrial utilization of seaweeds in the past, present, and future. Proceedings of the 9th International Seaweed Symposium, Santa Barbara, California, August 20-27, 1977: 17-34.

Kwak, J. C. T, A. L. Ayub, and J. D. Sheppard. 1986. The role of colloid science in peat dewatering: Principles and Dewatering studies. *In:* Fuchsman, C. H. (ed.). Peat and Water. Elsevier Applied Science Publishers, Amsterdam. pp. 95-118.

Lockhart, N. C. 1983a. Electroosmotic dewatering of clays. I. influence of voltage. Colloids and Surfaces 6: 229-238.

Lockhart, N. C. 1983b. Electroosmotic dewatering of clays. II. influence of salt, acid, and flocculants. Colloids and Surfaces 6: 239-251.

Lockhart, N. C. 1983c. Electroosmotic dewatering of clays. III. influence of clay type, exchangeable cations, and electrode materials. Colloids and Surfaces 6: 253-269.

Lockhart, N. C. 1986. Electro-dewatering of fine suspensions. *In:* Muralidhara, H. S. (ed.). Advances in Solid-Liquid Separations. Battelle Press, Columbus Ohio. pp. 241-274.

Lockhart, N. C. and G. H. Hart. 1988. Electro-osmotic dewatering of fine suspensions: The efficacy of current interruptions. Drying Technology 6(3): 415-423.

Muralidhara, H. S. 1988a. Combined fields dewatering. Proceedings of IDS-88, Versailles, France: KL.71-76.

Muralidhara, H. S. 1988b. The combined field approach to separations. Chemtech 18(4): 229-235.

Muralidhara, H. S., H. Hampel, and H. Kroening. 1988. Dewatering of Hamburg's dredged material by electroacoustic dewatering. Drying Technology 6(3): 535-546.

Murakami, Y., K. Nisizawa, K. Awaya, S. Suzuki, and S. Ideda. 1983. Utilization of burst algal meal as feed for domestic animals and fowls. Proceedings of the 11th International Seaweed Symposium, Qingdao, China, June 19-25, 1983: 101-105.

Nebb, H. and A. Jensen. 1965. Seaweed meal as a source of minerals and vitamins in rations for dairy cows and bacon pigs. Proceedings of the 5th International Seaweed Symposium, Halifax, Nova Scotia, August 25-28, 1965: 387-393.

Nelson, W. R. and J. Van Staden. 1984a. The effect of seaweed concentrate on growth of nutrient stressed greenhouse cucumbers. HortScience 19(1): 81-82.

Nelson, W. R. and J. Van Staden. 1984b. The effect of seaweed concentrate on wheat culms. Journal of Plant Physiology 115: 433-437.

Nelson, W. R. and J. Van Staden. 1986. Effect of seaweed concentrate on the growth of wheat. South African Journal of Science 82: 199-200.

Oprin, C. G., Y Greenwood, F. J. Hall, and I. W. Paterson. 1985. The rumen microbiology of seaweed digestion in Orkney sheep. Journal of Applied Bacteriology 59: 585-596.

Porta, A. 1986. Scale-up aspects of electro-osmotic dewatering. *In:* Muralidhara, H. S. (ed.). Advances in Solid-Liquid Separation. Battelle Press, Columbus Ohio. pp. 275-290.

Povolny, M. 1969. Einflus des extraktes von seealgen auf die lagerungsfaehigkeit von aepfeln (english abstract only). Proceedings of the 6th International Seaweed Symposium, Santiago de Compostela, September 9-13, 1969: 703.

Povolny, M. 1974. The effect of the steeping of peat-cellulose flowerpots (jiffypots) in extracts of seaweeds on the quality of tomato seedlings. Proceedings of the 8th International Seaweed Symposium, Bangor, North Wales, August 18-23, 1974: 730-733.

Ratan, R., B. C. Patnayak, and D. R. Bhatia. 1979. A note on the utilization of seaweed-meal (*Sargassum*) in concentrate mixture of cross-bred hoggets. Indian Journal of Animal Science 49(2): 140-142.

Rosell, K. G. and L. M. Srivastava. 1984. Seasonal variation in the chemical composition of the brown algae *Macrocystis integrifolia* and *Nereocystis luetkeana*. Canadian Journal of Botany 62(11): 2229-2236.

Senior, B. J., P. Collins, and M. Kelly. 1946. The feeding value of seaweeds. Economic Proceedings of the Royal Dublin Society 4(19): 273-285.

Skelton, B. J. and T. L Senn. 1969. Effect of seaweed sprays on quality and shelf-life of peaches. Proceedings of the 6th International Seaweed Symposium, Santiago de Compostela, September 9-13, 1969: 731-735.

Smidsrφd, O. and H. Grasdalen. 1983. Polyelectrolytes from seaweeds. Proceedings of the 11th International Seaweed Symposium, Qingdao, China, June 19-25, 1983: 19-28.

Stephenson, W. M. 1965. The effect of hydrolysed seaweed on certain plant pests and diseases. Proceedings of the 5th International Seaweed Symposium, Halifax, Nova Scotia, August 25-28, 1965: 405-415.

Stephenson, J. W. 1974. The effects of seaweed extract on the yield of a variety of field and glasshouse crops. Proceedings of the 8th International Seaweed Symposium, Bangor, North Wales, August 18-23, 1974: 740-744.

Sunderland, J. G. 1988. Electrokinetic dewatering of ball clay. Drying Technology 6(3): 425-445.

Tarjan, A. C. 1977. Kelp derivatives for nematode-infected citrus trees. Journal of Nematology 9(4): 287.

Temple, W. D. and A. A. Bomke. 1988. Effects of kelp (*Macrocystis integrifolia*) on soil chemical properties and crop response. Plant and Soil 105: 213-222.

Temple, W. D. and A. A. Bomke. 1989. Effects of kelp (*Macrocystis integrifolia* and *Ecklonia maxima*) foliar applications on bean growth. Plant and Soil 117: 85-92.

Temple, W. D., A. A. Bomke, R. A. Radley, and F. B. Holl. 1989. Effects of kelp (*Macrocystis integrifolia* and *Ecklonia maxima*) foliar applications on bean growth and nitrogen nutrition under varying soil moisture regimes. Plant and Soil 117: 75-83.

Tribe, D. E. and E. M. Tribe. 1949. Sheep-grazing seaweed: Observations on North Ronaldshay, Orkney Is. Agriculture 56: 416-419.

Waaland, J. R. 1981. Commercial utilization. *In:* Lobban, C. S. and M. J. Wynne (eds.). The Biology of Seaweeds. University of California Press, Berkely and Los Angeles. pp. 726-740.

Whittemore, C. T. and J. K. Percival. 1975. A seaweed residue unsuitable as a major source of energy or nitrogen for growing pigs. Journal of the Science of Food and Agriculture 26: 215-217.

Whyte, J. N. C. and J. R. Englar. 1974a. Commercial kelp drying operation at Masset, 1973. Fisheries Research Board of Canada Technical Report No. 453: 30 pp

Whyte, J. N. C. and J. R. Englar. 1974b. Elemental composition of the marine alga *Nereocystis luetkeana* over the growing season. Department of the Environment, Fisheries and Marine Service, Technical Report No. 509: 29 pp.

Whyte, J. N. C. and J. R. Englar. 1975. Basic organic chemical composition of the marine alga *Nereocystis luetkeana* over the growing season. Department of the Environment, Fisheries and Marine Service, Technical Report No. 589: 42 pp.

Whyte, J. N. C., J. R. Englar, and T. Nishihama. 1974. Chemical constituents of *Nereocystis luetkeana*. Proceedings of the 8th International Seaweed Symposium, Bangor, North Wales, August 18-23, 1974: 644-649.

Whyte, J. N. C., J. R. Englar, and P. E. Borgman. 1981. Compositional changes on freshwater leaching of the marine algae *Nereocystis luetkeana* and *Macrocystis integrifolia*. Canadian Journal of Fisheries and Aquatic Sciences 38(2): 193-198.

Williams, D. C., K. R. Brain, G. Blunden, and P. B. Wildgoose. 1974. Plant growth regulatory substances in commercial seaweed extracts. Proceedings of the 8th International Seaweed Symposium, Bangor, North Wales, August 18-23, 1974: 760-763.

Wilczek, C. A. and T. J. Ng. 1982. Promotion of seed germination in table beet by an aqueous seaweed extract. HortScience 17(4): 629-630.

Yoshida, H. and H. Yukawa. 1988a. Electroosmotic dewatering process and design equations. Drying Technology 6(3): 389-414.

Yoshida, H. and H. Yukawa. 1988b. A theoretical analysis of the electro-osmotic dewatering of sludge. International Chemical Engineering 28(3): 477-485.

Yukawa, H., K. Kobayashi, H. Yoshida, and M. Iwata. 1979. Studies of electrically enhanced sedimentation, filtration and dewatering processes. *In:* Wakeman, R. J. (ed.). Progress in Filtration and Separation. Elsevier Scientific, New York. pp. 83-112.

VIII. APPENDICES

Appendix A - Complete Statistical Analysis Results

Table A.1. Analysis of variance of press cake percent solids for pretreatment-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	15	45.3294			
Pretreatment	3	27.7719	9.2573	88.69**	0.0001
Current	1	16.2006	16.2006	155.22**	0.0001
P * C	3	0.5219	0.1740	1.67[NS]	0.25
Error	8	0.8350	0.1044		

**Significant at 0.01 level
[NS]Not significant at 0.05 level

<u>Duncan's Multiple Range Test</u>

Pretreatment	Mean
None	10.475_a
Heat	11.800_b
$CaCl_2$	12.000_b
$CaCl_2$ and Heat	14.150_c

Means with the same letter are not significantly different.

Table A.2. Analysis of variance of press cake percent solids for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	38.3596			
Pressure	2	17.9733	8.9867	48.25**	0.0001
Current	3	12.4846	4.1615	22.34**	0.0001
P * C	6	5.6667	0.9444	5.07**	0.0082
Error	12	2.2350	0.1863		

**Significant at 0.01 level

<u>Duncan's Multiple Range Test</u>

Pressure	Mean
7.46	12.488_a
34.6	13.788_b
104.0	14.588_c

Current	Mean
0.00	12.833_a
0.33	13.100_a
0.67	13.867_b
1.00	14.683_c

Means with the same letter within each grouping are not significantly different.

Table A.3. Analysis of Variance of filtrate percent solids for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	0.6796			
Pressure	2	0.1058	0.0529	2.23^{NS}	0.1504
Current	3	0.2246	0.0749	3.15^{NS}	0.0646
P * C	6	0.0642	0.0107	0.45^{NS}	0.8315
Error	12	0.2850	0.1863		

^{NS}Not significant at 0.05 level

Table A.4. Analysis of variance of total mass remaining in press cake for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	2099.0250			
Pressure	2	966.9486	483.4743	26.49^{**}	0.0001
Current	3	627.4003	209.1334	11.46^{**}	0.0008
P * C	6	285.6989	47.6165	2.61^{NS}	0.0742
Error	12	218.9772	18.2481		

**Significant at 0.01 level
^{NS}Not significant at 0.05 level

Duncan's Multiple Range Test

Pressure	Mean (g)	Current	Mean (g)
7.46	76.75_a	0.33	72.88_a
34.6	65.62_b	0.00	71.86_a
104.0	61.11_b	0.67	65.73_b
		1.00	60.18_c

Means with the same letter within each grouping are not significantly different.

Table A.5. Analysis of variance of mass of solids remaining in press cake for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	6.7031			
Pressure	2	2.0473	1.0237	8.76**	0.0045
Current	3	2.1408	0.7136	6.11**	0.0092
P * C	6	1.1124	0.1854	1.59[NS]	0.2335
Error	12	1.4026	0.1169		

**Significant at 0.01 level
[NS]Not significant at 0.05 level

Duncan's Multiple Range Test

Pressure	Mean (g)	Current	Mean (g)
7.46	9.50_a	0.33	9.50_a
34.6	8.98_b	0.67	9.20_{ab}
104.0	8.82_b	0.00	9.03_{bc}
		1.00	8.67_c

Means with the same letter within each grouping are not significantly different.

Table A.6. Analysis of variance of mass of water remaining in press cake for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	1880.2612			
Pressure	2	880.5162	440.2581	28.02**	0.0001
Current	3	559.3243	186.4414	11.87**	0.0007
P * C	6	251.8841	41.9807	2.67NS	0.0695
Error	12	188.5370	15.7114		

**Significant at 0.01 level
NSNot significant at 0.05 level

Duncan's Multiple Range Test

Pressure	Mean (g)	Current	Mean (g)
7.46	66.75_a	0.33	63.38_a
34.6	56.64_b	0.00	62.66_a
104.0	52.29_c	0.67	56.70_b
		1.00	51.51_c

Means with the same letter within each grouping are not significantly different.

Table A.7. Analysis of variance of filtrate pH for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	20.8396			
Pressure	2	1.1008	0.5504	2.45^{NS}	0.1281
Current	3	14.6479	4.8826	21.74^{**}	0.0001
P * C	6	2.3958	0.3993	1.78^{NS}	0.1865
Error	12	2.6950	0.2246		

**Significant at 0.01 level
^{NS}Not significant at 0.05 level

Duncan's Multiple Range Test

Current	Mean
0.00	5.550_a
0.33	4.517_b
0.67	3.750_c
1.00	3.567_c

Means with the same letter are not significantly different.

Table A.8. Analysis of variance of electrical energy for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	838.9520			
Pressure	2	1.6126	0.8063	2.64^{NS}	0.1119
Current	3	832.2643	277.4214	909.53^{**}	0.0001
P * C	6	1.4149	0.2358	0.77^{NS}	0.6058
Error	12	3.6602	0.3050		

**Significant at 0.01 level
^{NS}Not significant at 0.05 level

Duncan's Multiple Range Test

Current	Mean (kJ)
0.00	0.00_a
0.33	4.61_b
0.67	10.03_c
1.00	15.73_d

Means with the same letter are not significantly different.

Table A.9. Analysis of variance of mechanical energy for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	114.6882			
Pressure	2	106.1561	53.0780	148.25^{**}	0.0001
Current	3	1.3869	0.4623	1.29^{NS}	0.3222
P * C	6	2.8489	0.4748	1.33^{NS}	0.3181
Error	12	4.2963	0.3580		

**Significant at 0.01 level
^{NS}Not significant at 0.05 level

Duncan's Multiple Range Test

Pressure	Mean (J)
7.46	0.070_a
34.6	0.868_b
104.0	4.877_c

Means with the same letter are not significantly different.

Table A.10. Analysis of variance of percent ash in press cake for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	231.0955			
Pressure	2	34.5073	17.2536	2.57^{NS}	0.1176
Current	3	57.4708	19.1569	2.86^{NS}	0.0816
P * C	6	58.6334	9.7722	1.46^{NS}	0.2722
Error	12	80.4841	6.7070		

^{NS}Not significant at 0.05 level

Table A.11. Analysis of variance of percent original ash retained in press cake for pressure-current combinations.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	23	1175.8400			
Pressure	2	213.9375	106.9688	5.30*	0.0224
Current	3	409.5200	136.5067	6.77**	0.0064
P * C	6	310.2925	51.7154	2.56^{NS}	0.0779
Error	12	242.0900	20.1742		

**Significant at 0.01 level
*Significant at 0.05 level
^{NS}Not significant at 0.05 level

Duncan's Multiple Range Test

Pressure	Mean	Current	Mean
7.46	52.38_{a}	0.33	54.65_{a}
34.6	48.81_{ab}	0.00	50.18_{ab}
104.0	45.06_{b}	0.67	46.58_{bc}
		1.00	43.58_{c}

Means with the same letter within each grouping are not significantly different.

Table A.12. Analysis of variance of percent ash for untreated kelp, conventionally dewatered kelp, and combined fields dewatered kelp.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	134.5783			
Treatment	2	123.6321	61.8161	16.94*	0.0232
Error	3	10.9462	3.6487		

*Significant at 0.05 level

Duncan's Multiple Range Test

Treatment	Mean
None	39.39_a
Conv. DW	31.70_b
Comb. Field DW	28.59_b

Means with the same letter are not significantly different.

Table A.13. Analysis of variance of percent fat for untreated kelp, conventionally dewatered kelp, and combined fields dewatered kelp.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	2.4013			
Treatment	2	1.0760	0.5380	1.22^{NS}	0.4100
Error	3	1.3253	0.4418		

^{NS}Not significant at 0.05 level

Table A.14. Analysis of variance of percent protein for untreated kelp, conventionally dewatered kelp, and combined fields dewatered kelp.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	5.4807			
Treatment	2	3.8117	1.9059	3.43^{NS}	0.1680
Error	3	1.6690	0.5563		

^{NS}Not significant at 0.05 level

Table A.15. Analysis of variance of percent available carbohydrates for untreated kelp, conventionally dewatered kelp, and combined fields dewatered kelp.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	1.3389			
Treatment	2	1.3260	0.6630	154.79^{**}	0.0009
Error	3	0.0129	0.0043		

**Significant at 0.01 level

Duncan's Multiple Range Test

Treatment	Mean
None	1.865_a
Conv. DW	0.790_b
Comb. Field DW	0.970_b

Means with the same letter are not significantly different.

Table A.16. Analysis of variance of percent uronic acid for untreated kelp, conventionally dewatered kelp, and combined fields dewatered kelp.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	49.2117			
Treatment	2	7.2121	3.6061	0.26[NS]	0.7884
Error	3	41.9996	13.9999		

[NS]Not significant at 0.05 level

Table A.17. Analysis of variance of percent ash for untreated kelp and dewatered kelp from combined fields roller press.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	224.5498			
Treatment	1	224.3594	224.3594	4713**	0.0001
Error	4	0.1904	0.0476		

**Significant at 0.01 level

Table A.18. Analysis of variance of percent fat for untreated kelp and dewatered kelp from combined fields roller press.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	1.5467			
Treatment	1	0.0451	0.0451	0.12NS	0.7464
Error	4	1.5016	0.3754		

NSNot significant at 0.05 level

Table A.19. Analysis of variance of percent protein for untreated kelp and dewatered kelp from combined fields roller press.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	15.5279			
Treatment	1	14.1988	14.1988	42.73**	0.0028
Error	4	1.3291	0.3323		

**Significant at 0.01 level

Table A.20. Analysis of variance of percent available carbohydrate for untreated kelp and dewatered kelp from combined fields roller press.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	1.6459			
Treatment	1	0.6468	0.6468	2.59^{NS}	0.1828
Error	4	0.9991	0.2498		

^{NS}Not significant at 0.05 level

Table A.21. Analysis of variance of percent uronic acid for untreated kelp and dewatered kelp from combined fields roller press.

Source	DF	Sum of Squares	Mean Square	F-Value	p > F
Corr. Total	5	11.9642			
Treatment	1	0.5046	0.5046	0.18^{NS}	0.6963
Error	4	11.4596	2.8649		

^{NS}Not significant at 0.05 level

Appendix B - Results of Statistical Modelling

Table B.1. Linear model fit to total mass remaining in press cake.

Parameter	Estimate	T for H_0: Parameter = 0	$p > T$
Intercept	80.7415	31.17^{**}	0.0001
Current	-12.6503	-3.75^{**}	0.0012
Pressure	-0.1387	-4.48^{**}	0.0002

**Significant at 0.01 level

$R^2 = 0.6188$

Table B.2. Linear-log model fit to total mass remaining in press cake.

Parameter	Estimate	T for H_0: Parameter = 0	$p > T$
Intercept	93.7757	23.85^{**}	0.0001
Current	-12.6503	-4.28^{**}	0.0003
Log(Pres.)	-5.8214	-5.70^{**}	0.0001

**Significant at 0.01 level

$R^2 = 0.7075$

Table B.3. Linear model fit to mass of water remaining in press cake.

Parameter	Estimate	T for H_0: Parameter = 0	p > T
Intercept	71.0331	29.35**	0.0001
Current	-12.0330	-3.82**	0.0010
Pressure	-0.1326	-4.58**	0.0002

**Significant at 0.01 level

$R^2 = 0.6285$

Table B.4. Linear-log model fit to mass of water remaining in press cake.

Parameter	Estimate	T for H_0: Parameter = 0	p > T
Intercept	83.4687	22.84**	0.0001
Current	-12.0330	-4.38**	0.0003
Log(Pres.)	-5.5574	-5.85**	0.0001

**Significant at 0.01 level

$R^2 = 0.7180$

Appendix C - Material Balance Calculations

Given: 165 g of material (150 g of kelp, 15 g of 5% $CaCl_2$ solution)
s_o = original solids of kelp and $CaCl_2$ solution
s_{cake} = solids of press cake
$s_{filtrate}$ = solids of filtrate

total mass of solids in = total mass of solids out

$$165\, s_o = m_{cake}\, s_{cake} + (165 - m_{cake})\, s_{filtrate}$$

$$m_{cake} = \frac{165\,(s_o - s_{filtrate})}{(s_{cake} - s_{filtrate})}$$

$$m_{solids} = m_{cake}\, s_{cake}$$

$$m_{water} = m_{cake}\,(1 - s_{cake})$$

where m_{cake} is the total mass remaining in the press cake, m_{solids} is the mass of solids remaining in the press cake, and m_{water} is the mass of water remaining in the press cake.