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Dewatering, Metal Removal, Pathogen Elimination, and Organic Matter Reduction in Biosolids Using Electrokinetic Phenomena

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Abstract

Dewatering, Metal Removal, Pathogen Elimination, and Organic Matter Reduction in Biosolids Using Electrokinetic Phenomena

Ali Esmaeily

Municipal and industrial wastewater treatment plants (WWTP) produce sludge that contains around 5 % of solids. Sludge requires further treatment before final disposal, which is limited because of the contents of heavy metals, nutrients, and some pathogens. A solution for more efficient biosolids management is urgent. The main objective of this study is revitalization of biosolids focussing on dewatering, metals and organic matter reduction as well as pathogen destruction to reduce the hazard associated with disposal or reuse. Subsequently a new cost-effective method combining all processes into one technology is investigated. The feasibility of using electrokinetic processes was evaluated out at lab scale. Six cells were filled up with biosolids from the WWTP in Laval (Quebec). Di-ammonium- phosphate was added to two cells. The DC power supply was connected to 5 cells (one cell was left without connection as a control cell) and the desirable potential gradients were set up at 0.5 V/cm, 1.0 V/cm, and 1.5 V/cm in respective cells. During 10 days of experiment, electrical parameters were measured and water was collected from the cathode area. At the end of the experiment, the biosoilds were subjected to physico-chemical analysis. No fecal coliforms were observed in cells with fertilizer. Results showed the capability of dewatering by 95 %. The highest solids content was achieved in the cell with the highest voltage in the presence of fertilizer. The removal of organic matter reached 47%. The experiment showed the best removal for lead (below detection limit). The transport of other metals (Cu, Ni, Zn, Cd, and Fe) was

also observed. For the optimal removal condition, which is in the cell with potential 1.5 V/cm in the presence of fertilizer, the consumption of energy was 220 $kW.h/m^3$ of biosolids or \$ $6.62/m^3$ of biosolids.

Acknowledgements

I am deeply indebted to my supervisor Prof. Dr. Maria Elektorowicz for her precious instruction. Her dynamic thinking, her broad and profound knowledge, her warm smile and her patient instruction have given me a great help.

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I wish to express my deepest appreciation to my parents who dedicated their whole life for my education. Finally, I would like to give my special thanks to my wife Shiva whose patient love and devotion enabled me to complete this work.

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Chapter 1

Introduction

1-1) Statement of the Problem

Municipal and industrial wastewater treatment plants (WWTP) produce treated water and sludge. Sewage sludge consists of 92 – 97 % of water and 3 – 8 % solids (Metcalf and Eddy, 1991). Primary treatment in WWTP separates suspended solids and greases from wastewater. Secondary treatment is a biological treatment process to remove dissolved organic matter from wastewater. Sewage microorganisms are cultivated and added to the wastewater. The microorganisms absorb organic matter from sewage as their food supply. Primary sludges, material that settles out during primary treatment, often have a strong odor and require treatment prior to disposal. Secondary sludges are the excess microorganisms from the biological treatment processes. The contemporary management of biosolids focuses on its revitalization as solids contain organic materials that can be useful after treatment and also contain energy that can be recovered. Even ash resulting from incineration can be used beneficially. However, a direct use of sludge is impossible due to the presence of some pollutants. Type of these pollutants depends on origin of wastes, additives, and processes that wastewater has been passed through. Subsequently, the biosolids that are removed and collected must be disposed in a safe and nuisance-free manner without hazard to health or environment.

The classical management of biosolids within WWTP consists of thickening, dewatering (to minimize the total volume to be handled) and biological treatment.

Sludge or biosolids dewatering process removes water, increases the concentration of solids, reduces weight and volume and prepares biosolids for further treatment and handling. Natural air drying and mechanical methods are two different categories for dewatering processes. Natural methods are able to remove water only in some extended (20%-30%) and they are time dependant. Disposal of pulp-like biosolids does not permit them to be used in landfarming and presents a danger for mobile heavy equipment. Mechanical methods are more controllable and faster (20% - 40% solids content) but much more costly. They use complicated equipment and usually they have operation problems.

In addition, the disposal of treated biosolids is limited due to the fact that they contain heavy metals, nutrients, and some pathogens. Subsequently, direct landfarming of dewatered biosolids presents a hazard for environment. The improvement of environmental standards leads to build up of more efficient WWTP, which subsequently generate more biosolids. A solution for more efficient biosolids management is urgent.

An efficient dewatering system with successful remediation of biosolids including disinfection and metal removal is the most expected new technology in environmental engineering.

1-2) Objectives

The main objective of this study is to evaluate the feasibility of using electrokinetics for dewatering, heavy metals removal, organic matter reduction and pathogen destruction of biosolids to reduce the hazard associated with disposal or reuse. The secondary objective is presenting a cost-effective method due to combining of all processes in one technology.

To achieve the goals herein described, the thesis is subdivided into the following chapters:

Chapter 1 contains statement of the problem and goals of this study.

In Chapter 2, a detailed evaluation based on literature review was performed in order to outline in detail the nature of problem under consideration.

Chapter 3 contains the methodology of the experiment as well as physical and chemical analysis of biosolids samples.

In Chapter 4, a discussion of the results obtained in this investigation is presented.

Chapter 5 contains conclusions and recommendations, which are based on the data, and the results obtained in the experiment.

Chapter 2

Literature Review

Production of biosolids has increased due to population growth so treatment and disposal of these solids are an urgent necessity. At the same, time recycling of biosolids (e.g. in agriculture) may improve the soil characteristics and decrease dependence on chemical fertilizer.

2-1) Biosolids Characteristics

"Sludge (biosolids) is composed of divers solid particles suspended in an impure water continuum. Attempts to characterize sludge (biosolids) 'particles' have been hampered by the fact that they are dynamic-dispersing and reforming, depending on biological, chemical, and physical conditions" (Vesilind, 1996).

As shown in Figure 2-1, water in biosolids exists in four phases: free water, colloidal water, intercellular water, and capillary water (Outwater, 1994).

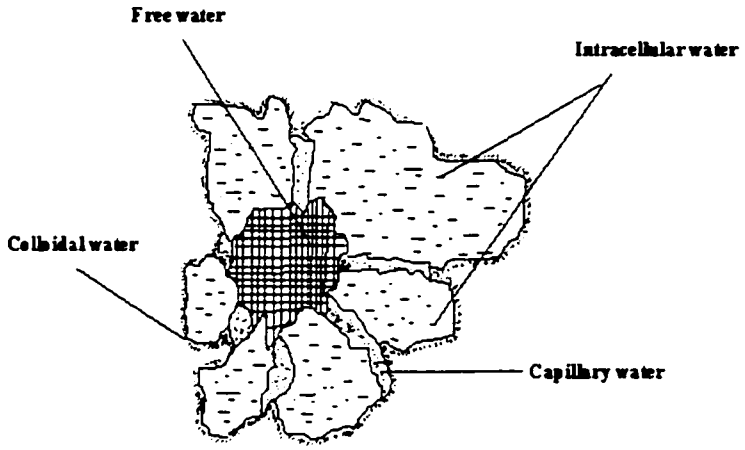


Figure 2-1 Distribution of water in a biosolids particle

Colloids are defined as having particle diameters less than 0.002 mm, which do not settle out from a suspension when left to stand. The small particle size permits formation of aggregates with a large specific surface area. Polar chemical groups and charges at the surface will govern interactions between the material and water or any dissolved substances.

Free water is not connected to and controlled by suspended solids and can be separated and removed by gravity without difficulty. Biosolids should be conditioned chemically first and then mechanical methods will be able to remove colloidal and capillary water. To separate the intracellular water, first the cell structure of biosolids must be broken which is usually done by thermal treatment (Vesilind, 1996).

Quality of dewatering depends on several items such as the source of biosolids and also prior units to dewatering that may affect biosolids characteristics. Therefore, in order to improve dewatering processes, usually biosolids are conditioned by various chemicals, thermal treatment processes, or through blending processes.

The biosolids' characteristics which have the most significant effects on dewatering are as follows (USEPA, 1982):

- pH: pH changes the surface charge of biosolids particles. The type of polymer, which is used for conditioning, will be determined by this factor. This is recommended to use cationic polymers for pH level below natural (and slightly above) and anionic polymers for high pH.
- Volatile solids to fixed solids ratio: Dewatering is easier when percentage of fixed solids increased.
- Septicity: Dewatering needs more chemicals when they are stored septically.

- Temperature: Temperature of biosolids changes the viscosity of the water present in the biosolids. By increasing the temperature, the viscosity of the water decreases.
- Compressibility: Void space between particles is deformed and reduced by this factor so movement of water is inhibited which decreases the rate of dewaterability.
- Particle size: Biosolids sources and prior treatment influence particle size. The surface area of biosolids increases by decreasing of this factor. An increase in the surface area has the following effects:
    i. Electrical repulsion between biosolids particles will be increased due to larger area of negative charged surface.
    ii. More attraction of water to the surface of particles due to increase in the number of adsorption sites.
- Particle surface charge and hydration: There are chemically bonds (hydrogen) between water and solids (negative charge). Therefore, removing the water is more difficult.

2-1-1) Heavy Metals

Biosolids contain different amounts of heavy metals such as copper, lead, nickel, cadmium, and zinc. Sources of these metals are wastewater originated from municipal, industrial and commercial units, and urban run off. Table 2-1 shows the range and median concentrations of trace metals in digested biosolids (Walker, 1998).

Tertiary or advanced wastewater treatments are new technologies that could be used for metal removal from sludges. These methods need additional energy so due to enormous costs they are not applied in WWTP.

Table 2-1 Range and median concentration of metals in dry digested biosolids (Walker, 1998)

Element	Minimum Conc. (mg/kg)	Maximum Conc. (mg/kg)	Median Conc. (mg/kg)
As	1.1	230	10
Cd	1	3 410	10
Co	11.3	2 490	30
Cu	84	17 000	800
Cr	10	99 000	500
F	80	33 500	260
Fe	1 000	154 000	17 000
Hg	0.6	56	6
Mn	32	9 870	260
Mo	0.1	214	4
Ni	2	5 300	80
Pb	13	26 000	500
Sn	2.6	329	14
Se	1.7	17.2	5
Zn	101	49 000	1 700

2-1-2) Nitrogen and Phosphorus

Nitrogen and phosphorus are two important compounds that have received increased attention due to their impact on unwanted growth of algae and aquatic plants.

Nitrogen is present mostly in the form of organic nitrogen or ammonia nitrogen. The Kjeldahl method is used to measure the organic nitrogen that involves a digestion step to convert the organic nitrogen to ammonia and then analysis of ammonia by titration. The nitrate level can be measured by colorimetric or potentiometric methods.

The main sources of phosphorus are urine and detergents. The major portion of phosphorus is inorganic in the form of orthophosphates (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$). Phosphorus is measured mostly by a colorimetric method. In this method other phosphates are converted to orthophosphates and then orthophosphates are determined (Carberry et al, 1983).

2-1-3) Pathogen

The principle for defining the quality of biosolids should be on the basis on the risk to human, animal and plant life. The level of pathogens should not exceed the ambient levels in the environment. In practice this means for the purposes of quality control realistic limits of defined pathogens must be set.

The quantity and species of pathogens in sewage sludge can vary considerably both with time and location depending upon local circumstances and the current health of the local population.

There are four major types of human pathogenic organisms found in biosolids: (1) bacteria, (2) viruses, (3) protozoa, and (4) helminths (parasitic worms). Table 2-2 (Metcalf and Eddy, 1991) summarizes the principal categories of pathogenic organisms found in wastewater. The concentration of organisms in biosolids depends on the type and concentration of pathogens present in the source of sewage and the degree to which those organisms are removed or eliminated by the pre-treatment processes (PDEP, 1998).

Table2-2 Infectious agents potentially present in raw domestic wastewater (Metcalf and Eddy, 1991)

Organism		Disease	Symptoms
Bacteria			
	Escherichia coli (enteropathogenic)	Gastroenteritis	Diarrhea
	Legionella pneumophila	Legionellosis	Acute respiratory illness
	Leptospira (150 spp.)	Leptospirosis	Jaundice, fever (weil's disease)
	Salmonella typhi	Typhoid fever	High fever, diarrhea, ulceration of small intestine
	Salmonella (~1 700 spp.)	Salmonellosis	Food poisoning
	Shigella (4 spp.)	Shigellosis	Bacillary dysentery
	Vibrio cholerae	Cholera	Extremely heavy diarrhea, dehydration
	Yersinia enterolitica	Yersinosis	Diarrhea
Viruses			
	Adenovirus (31 types)	Respiratory disease	
	Enteroviruses (67 types)	Gastroenteritis, heart anomalies, meningitis	
	Hepatitis A	Infectious hepatitis	Jaundice, fever
	Norwalk agent	Gastroenteritis	Vomiting
	Reovirus	Gastroenteritis	
	Rotavirus	Gastroenteritis	
Protozoa			
	Balantidium coli	Balantidiasis	Diarrhea, dysentery
	Cryptosporidium	Cryptosporidiosis	Diarrhea
	Entamoeba histolytica	Amebiasis (amoebic dysentery)	Prolonged diarrhea with bleeding, abscesses of the liver and small intestine
	Giardia lambia	Giardiasis	Mild to sever diarrhea, nausea, indigestion
Helminths			
	Ascaris lumbricoides	Ascarisis	Roundworm infestation
	Enterobius vericularis	Enterobiasis	Pinworm
	Fasciola hepatica	Fascioliasis	Sheep liver fluke
	Hymenolepis nana	Hymenolepiasis	Dwarf tapeworm
	Taenia saginata	Taeniasis	Beef tapeworm
	T. solium	Taeniasis	Pork tapeworm
	Trichuris trichiura	Trichuriasis	Whipworm

2-2) Biosolids Management

2-2-1) Biosolids Dewatering

Reducing moisture and consequently the volume of biosolids for economical disposal or reuse is very important. Volume reduction also reduces the capacity of downstream operations (Shimp, 1995). An example of economical benefit of dewatering biosolids is land application. Metcalf and Eddy (1991) gave one of the best summaries as follows:

1. "The cost of transporting biosolids to the ultimate disposal site is greatly reduced when biosolids, volume is reduced;
2. Dewatered biosolids allows for easier handling;
3. Dewatering biosolids (reduction in moisture content) allows for more efficient incineration;
4. If composting is the beneficial reuse choice, dewatered biosolids decreases the amount and therefore the cost of bulking agents;
5. With the USEPA's 503 rule, dewatering biosolids may be required to render biosolids less offensive;
6. When landfill is the ultimate disposal option, dewatering biosolids is required to reduce leachate production."

Natural air drying and mechanical methods are two different categories for dewatering processes (USEPA, 1987). In natural methods, moisture is removed by evaporation and gravity such as sand beds, biosolids lagoons, paved beds, reed beds, vacuum-assisted beds, wedge water beds, and dewatering via freezing. Natural methods are usually cheaper than mechanical methods but mechanical methods are more

controllable. In addition, since natural methods depend on solar energy, gravity or biological processes they require less energy. Most common mechanical dewatering processes include pressure filters, vacuum filter, belt filter, and centrifuges.

The following factors are very important in selecting the most appropriate process:

- environmental benefits
- economic benefit
- time saving
- cost saving.

A brief description of some common dewatering methods is as follows.

2-2-1-1) Gravity / Low Pressure Dewatering

This method because of its simplicity and relatively low cost compared to the following methods, is suitable for small wastewater treatment plant.

Gravity and low pressure dewatering devices typically produce a biosolids cake with a solids concentration in the range of 8 to 12 percent. These devices depend on large dosages of chemicals to condition the biosolids. Gravity and low pressure dewatering devices are very useful where a large biosolids volume reduction is needed. In these methods biosolids are concentrated by gravity drainage or gravity drainage in combination with low pressure pressing devices. If ultimate disposal of biosolids is land application, these methods are well suited especially if spreading is by truck or subsurface injection.

Gravity dewatering devices have a cylindrical unit covered with an interior filter media. Because of rotating these cylinders, conditioned biosolids are exposed to clean filter media continuously.

Low-pressure belt presses are much cheaper than the high-pressure belt presses. Biosolids cakes have lower contents of solids in low-pressure belt presses. The content depends on the chemical dosage and biosolids type. Figure 2-2 shows a sample of low-pressure belt press (Franklin, 1997).

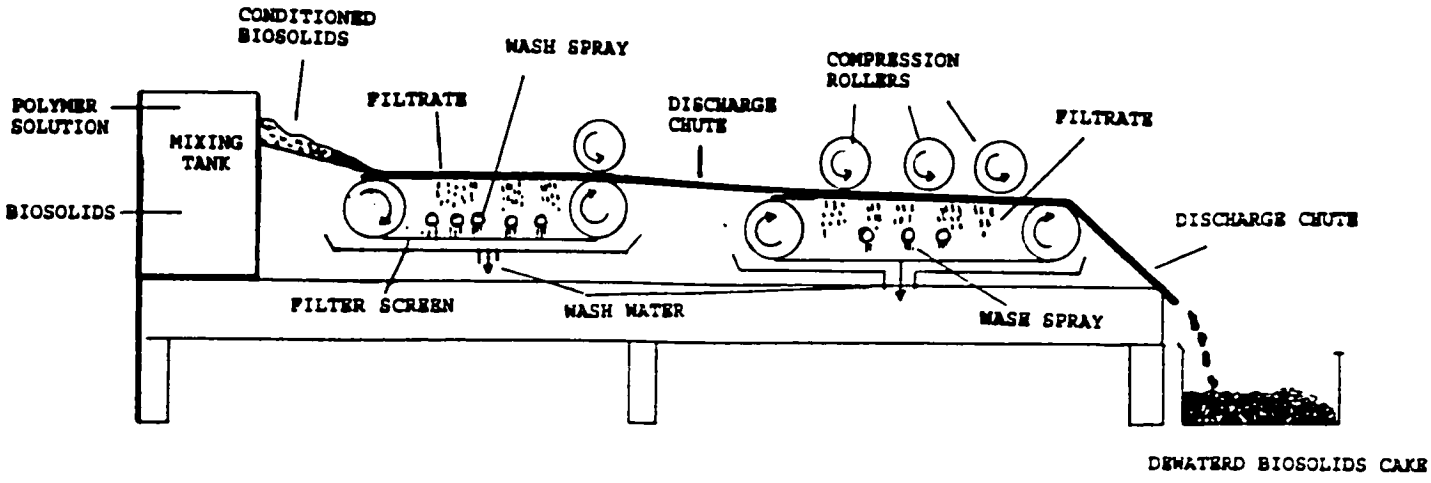


Figure 2-2 Low-pressure belt press (Franklin, 1997)

These methods have three disadvantages as follows:

1- Usage of large amount of expensive chemical conditioners before dewatering.

2- These methods are suitable only for small wastewater treatment plants.

3- Metals removal and disinfection are not considered.

2-2-1-2) Biosolids Lagoons

There is a difference between sludge drying lagoons and sludge lagoons that are used as a primarily storage or as aerated lagoon that is one of the waste treatment methods. The depth of biosolids lagoons is about 0.5 to 1.3 m. This method does not need high labor work. Dewatering is done by evaporation and to increase the drying process, supernatant liquor is decanted. The supernatant liquor is fed back to the wastewater treatment plant. Periodically, labors should break up or remove the surface crust to insure that evaporation goes on.

This method is relatively cheap and simple but creates a bad odor. The land should be situated far from a residential area to prevent neighbors' complaints. In this method solids concentration is between 15 to 40 percent and can be higher in dry climates. Figure 2-3 shows a typical lagoon bed.

Taking care of equipment and dikes is necessary and also dike vegetation must be controlled. Sometimes odor and insect control are required. If untreated biosolids are transferred into the biosolids lagoon, odor problems probably arise. To control this problem, chemical treatment with chlorination or hydrated lime addition are applied.

The cost of land is the capital cost for drying lagoons. Other major items include the construction of the dikes, sealing the bottom (if needed), underdrainage (if used) and the other elements that may be constructed.

Capital costs depend on the methods for sludge loading and removal. Costs of labor, fuel and maintenance of sludge removal equipment are the major O & M (operation and maintenance) costs.

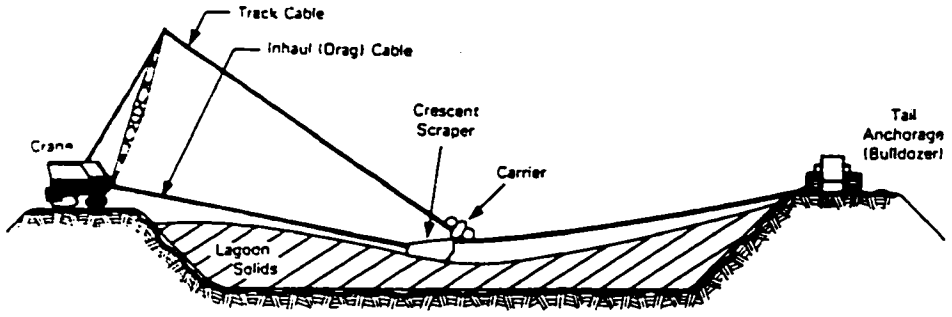


Figure 2-3 Lagoon bed (Orris, 1991)

Disadvantages of this method are odor, insect, dependence on climate, and possibility of groundwater contamination (Orris, 1991). The metal removal and disinfection are not considered in this type of biosolids management. This method is not applied for a large volume of biosolids.

2-2-1-3) Drying Beds

These methods are used for dewatering of biosolids that are well digested. The filtration system in biosolids drying beds usually consists of a gravel covered with sand, extruded plastic, or wire mesh. To increase the rate of dewatering process, a vacuum system can be added. As stated by Metcalf & Eddy (1991), there are four types of drying beds that are commonly used in dewatering biosolids including sand, paved, artificial media / wedgewater method, and vacuum assisted method.

- **Sand Drying Beds**

The sand drying bed is one of the oldest biosolids dewatering technique. There are 0.15 to 0.30 m of coarse sand underlaid by layers of graded gravel ranging from 0.003 to 0.006 m at the top and 0.008 to 0.015 m at the bottom. The thickness of the gravel usually is about 0.3 m. Wooden planks or concrete are usually used for sidewalls and partitions between bed sections. Figure 2-4 shows a typical sand drying bed.

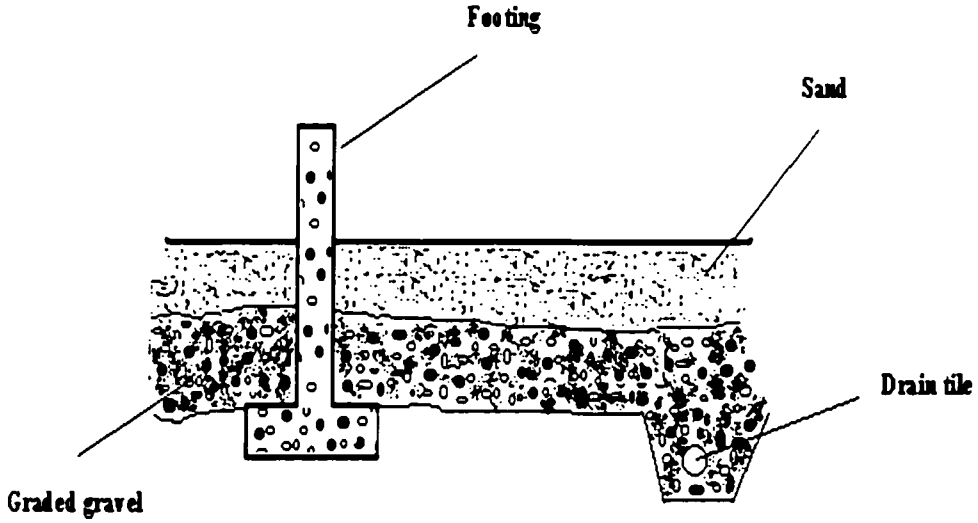


Figure 2-4 Sand drying bed

This method needs a large open area and at the smallest wastewater treatment plant, providing at least two drying beds is normal. The evaporation and drainage are the actual dewatering processes so the operation is affected by climate. Subsequently, the beds should be covered by translucent materials in wet climates. These materials allow passing through at least 85 % of the sun's ultraviolet radiation.

Time of drying depends on climate and season and can take a few weeks to a few months. In this method volume reduction is up to 85 % and the solids content in

dewatered biosolids is from 20 to 35 %. Dewatered biosolids by this method can be either incinerated or landfilled (Haller, 1995).

- **Paved Drying Beds**

Paved drying beds are paved with asphalt or concrete. Like biosolids lagoons, dewatering in paved drying beds depends on evaporation. These beds can be heated to increase the evaporation via buried pipes in the paved section. The depth of biosolids in the bed is usually around 0.30 m. To break up the crust and expose the wet surface to the environment, the surface is mixed routinely by special machines. Solids content in dewatered biosolids by this method is about 45 to 50 percent. It can take around 35 days in dry climates under normal conditions (Mc Ghee, 1991).

- **Artificial Media / Wedgewater Method**

Wedgewire beds look like vacuum assisted drying beds in the design. First, water is introduced to the bed to a level above the wire screen. After that, chemically conditioned biosolids are added to the system. The drain valve is open after a brief holding time and this process allows draining through the screen. Figure 2-5 shows the cross section of wedgewire drying bed. High capital costs, odor and low solids content (about 10 % dry biosolids) are the major disadvantages of this method (Metcalf & Eddy, 1991).

- **Vacuum-Assisted Drying Beds**

The vacuum-assisted drying bed is applied for small plants with limited area and small quantities of biosolids production. As shown in Figure 2-6, the porous medium is set above an aggregated-filled support underdrain. The small vacuum is applied to this underdrain that extracts free water from the biosolids.

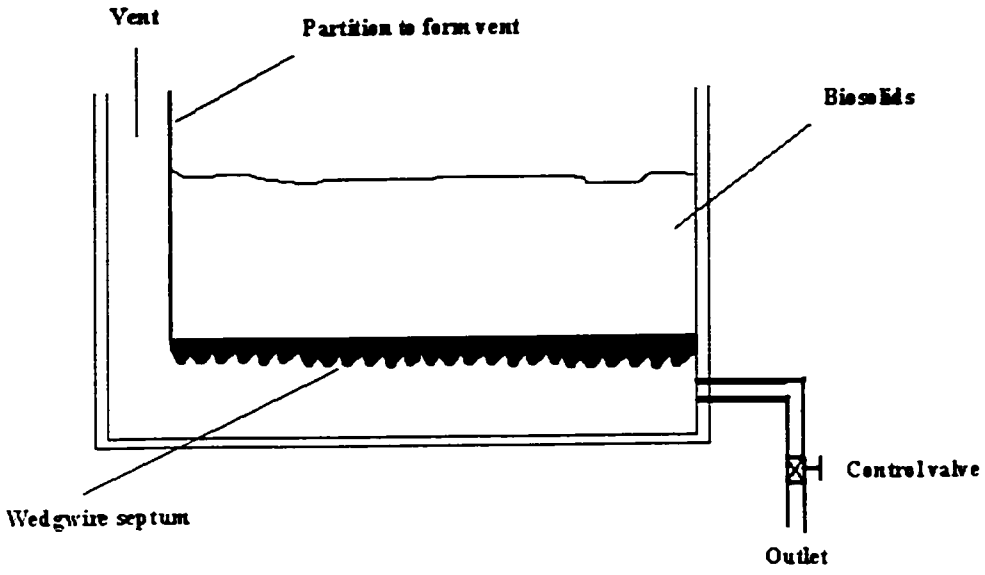


Figure 2-5 Wedgewire beds dewatering

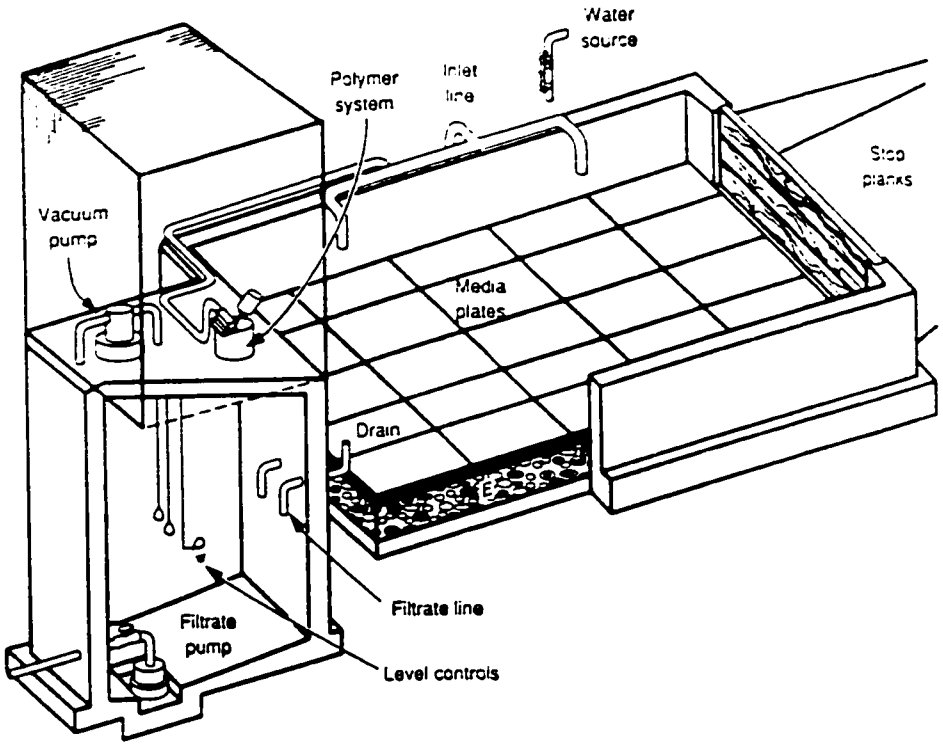


Figure 2-6 Vacuum assisted biosolids drying bed (Franklin, 1997)

According to McGhee (1991), operation's time for 10 kg/ m^2 of conditioned biosoilds is about one day. Solids content by this method is usually more than 20 %.

The time of dewatering in this method is relatively short. This method relies on adequate chemical conditioning for good dewatering (Metcalf & Eddy, 1991).

2-2-1-4) Freeze-Assisted Drying Beds

This method usually is used in cold climates during wintertime. The depth of frost penetration is a very important factor to determine the feasibility of freezing biosolids. To separate the free water, immediately after thawing the granular mass, the free water will be drained. During operation, the second layer will be applied soon after freezing of the first layer. Each layer should be frozen before applying the next layer.

"To ensure successful performances at all times, the design should be based on the warmest winter in the past 20 years and a layer which will freeze in a reasonable period of time if freeze-thaw cycles occur during the winter (Outwater, 1994)". This method is limited to cold climate.

2-2-1-5) Aquatic Plants

Reed beds are used in this method. In this system a sand drying bed is prepared and instead of removing the dewatered biosolids, reeds are planted in the bed and for several years biosolids are added to the bed. Figure 2-7 shows a typical reed bed (Franklin, 1997).

Phragmites reeds are known as the best choice for this application. These kinds of reeds are resistant to biosolids contaminants. The growing pattern of Phragmite reeds is very useful in the aquatic plant drying bed. The roots of Phragmite and several plants

branches grow vertically through the biosolids (Riggle, 1991). This vertical growing pattern provides channels that help in water drainage.

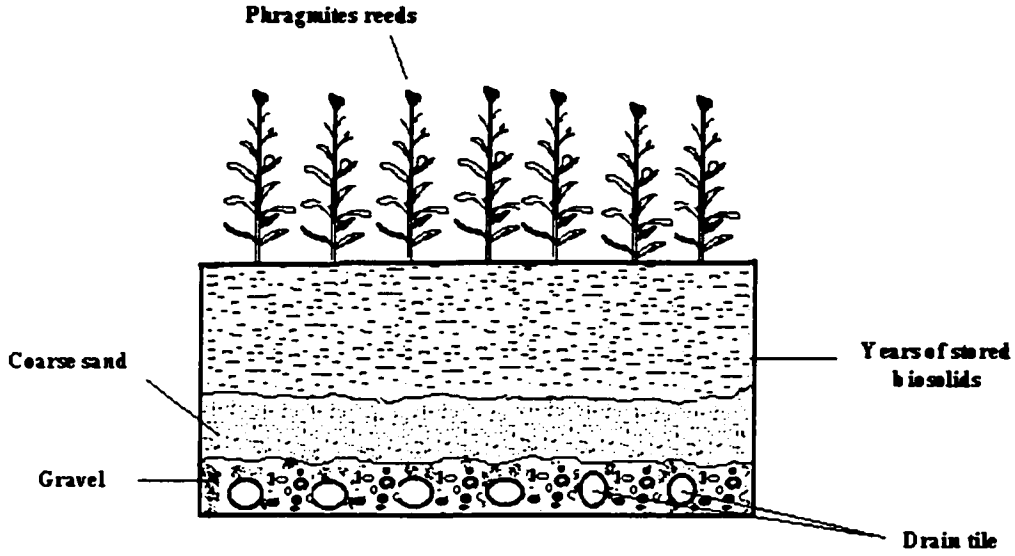


Figure 2-7 A typical reed bed

The reeds are harvested each fall but their roots system remains intact. After about 8 years, an average reed bed is filled. After that, to stabilize the top surface layer, the bed should be taken out of service. This method is suitable for small-scale biosolids production for operational reasons and also cost of land (Franklin, 1997).

2-2-1-6) Filter Process

In this method a positive pressure is used to force liquid through the filter media. Generally, filter presses have two categories including plate and frame and belt presses.

- **Plate and Frame**

The plate and frame press is a batch system. In this method individual plates that are covered with cloth, are placed side by side in frames. The plates are squeezed between moveable and fixed ends of the frame.

The continued pumping of biosolids causes the pressure forcing the water out of the biosolids. Filtrated water is returned to the plant for treatment. When filtrate flow stops, pumping is ceased too. After that plates are separated mechanically or automatically. Then dewatered biosolids are removed from the system and the plates are cleaned. Complexity, high labor costs, high chemical costs, and limitations on the woven filter cloths are disadvantages of this method that are listed by Metcalf & Eddy (1991).

- **Belt Press Filtration**

Operation of belt presses can be continues or batch. In this method, conditioned biosolids is sent to one end of the carrier belt. The two belts and biosolids travel between a series of rollers. In this operation biosolids is pressed between belts and this pressure squeezes the water out from the biosolids. Extracted water is returned to the wastewater treatment plant and dewatered biosolids is discharged onto a conveyor belt. Figure 2-8 shows a typical belt filter press (Girovich, 1996).

In this method biosolids are processed in three stages including chemical conditioning, gravity draining and compression shear. Each belt filter press includes a mixing drum, reactor drum, two-screen belt, a solid belt, a series of rollers, and washing belt system. Polymer solution and biosolids are mixed in the mixing drum and then this mixture enters the reactor drum. Most of free water is released in this drum.

Gravity, pressure, and shear pressure are the three stages of dewatering. The conditioned biosolids is discharged on the upper screen belt. This belt allows the water to drain off. Additional water is extracted on the upper screen belt by the pressure of the

solid belt on the conditioned biosolids. This pressure also distributes the biosolids over the width of the screen belt.

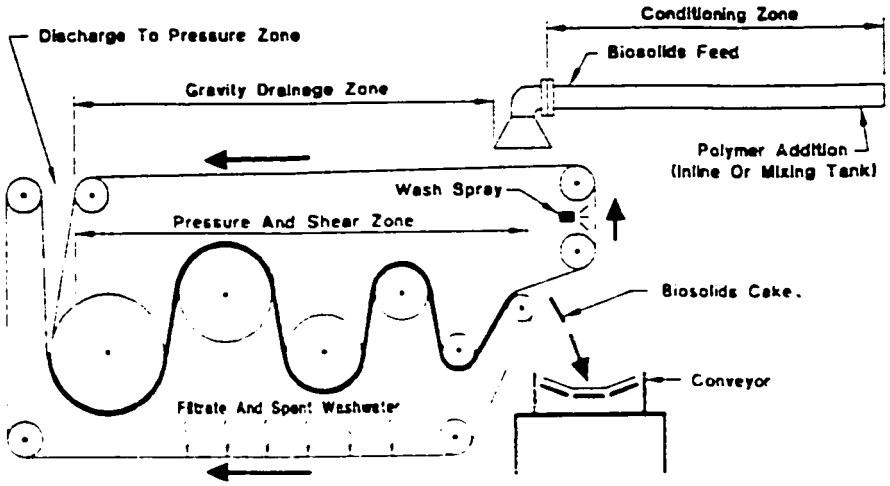


Figure 2-8 Belt filter press (Girovich, 1996)

Operation and capital costs of this method are generally less than other mechanical dewatering techniques. Belt filter presses are very sensitive to incoming feedback characteristics and chemical conditioning. A large quantity of wash water is needed for belt spraying (Girovich, 1996).

2-2-1-7) Vacuum Filtration

One of the most common mechanical dewatering processes for plants using trickling filter biological treatment unit, is vacuum filtration. This method includes a

horizontal cylindrical drum that is covered with a filtering material. This drum rotates partially submerged in a vat of conditioned biosolids.

The filter drum is divided into three compartments and each compartment is connected to a rotary valve. These compartments are cake formation zone, cake drying zone, and cake discharging zone. Figure 2-9 shows a typical vacuum filtration (Girovich, 1996).

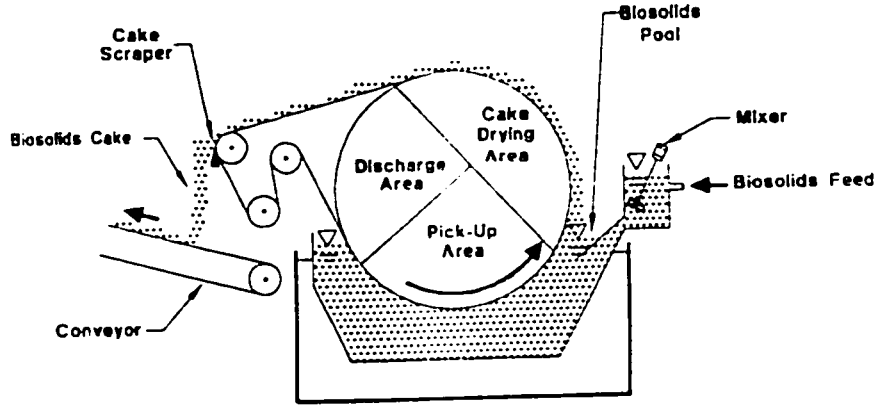


Figure 2-9 Vacuum filter (Girovich, 1996)

This drum is submerged to about 20 to 30 percent of its depth in the vat of conditioned biosolids. As the drum rotates, each section is successively carried through the cake formation zone to the cake-drying zone. Almost 40 to 60 percent of the drum surface is the cake-drying zone and this zone ends at the point where the internal vacuum is shut off. Solids concentration in this method ranges from 15 to 40 % (Girovich, 1996).

2-2-1-8) Centrifugation

The use of a centrifuge decreases the odor generation and requires less space in WWTP. The most important disadvantage for this method is that centrifugation has high power requirements so the power cost is high. Poor reliability of equipment is another disadvantage for centrifugation and the dewatering process depends on the quality of biosolids (Figure 2-10).

Development of improved polymers that create shear resistance floc allowing drier cakes at lower polymer dosages. Also development of high solids centrifuge technologies has increased cake solids content up to 25 to 40 percent. These are important advantages for this method.

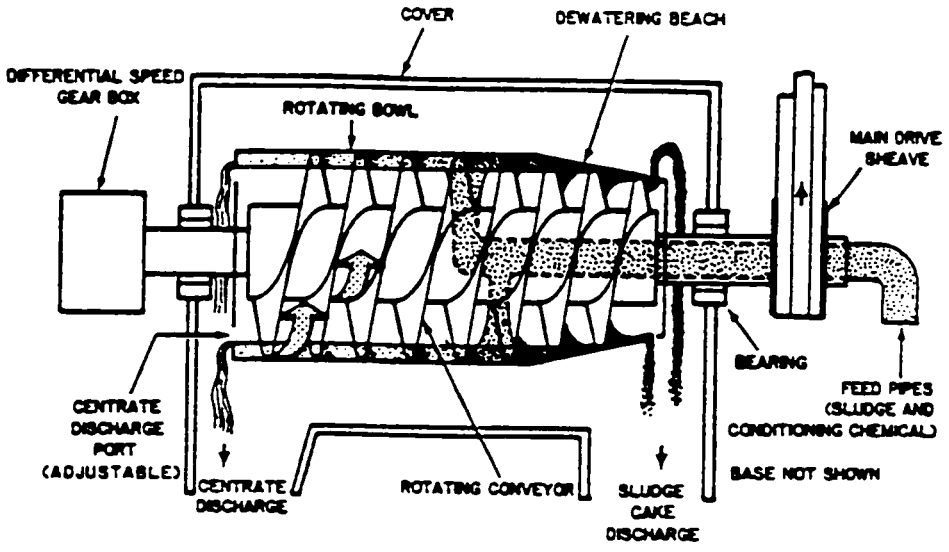


Figure 2-10 A countercurrent solid-bowl centrifuge (Robert, 1989)

Machines with relatively large pool volumes are most suitable for dewatering because of longer detention time and reduced forces on the sludge. Pool depths may be field-adjusted for improved clarification and biosolids cake drying (Robert, 1989). Less odor emissions, low maintenance and less labor requirements during operation are other advantages of this method.

2-2-1-9) Conclusion

Table 2-3 summarizes the solids content achievable by different dewatering techniques.

The above mentioned dewatering techniques which have been used conventionally have disadvantages and deficiencies, which can be summarized as follows:

- They only reduce water contents and do not improve the biosolids quality such as by reduction of heavy metals.
- The most efficient are the most costly.
- Some of them depend on the climate so they have numerous limitations.
- The pathogen removal is not solved in the present biosolids management methods.
- Labor cost is very high in most of these methods.
- To improve the biosolids quality, a cost-effective technology is needed.

Different technologies of dewatering of biosolids have been introduced but they are not successful enough. Some of these technologies have operation problems (e.g. filter pressure) and the others are quite costly (e.g. centrifuge).

Table 2-3 Percentage of achieved solids content using different dewatering techniques

Method	**Percentage of solids content after treatment**
Filter press	35 – 45
Drying beds	40
High solids centrifuge	25 – 40
Standard centrifuge	20 – 25
Lagoons / ponds	30
Vacuum filtration	25

Therefore there is a demand to explore and develop a new technology which will be more efficient and having more advantages. Since there is a huge increase in production of biosolids, the developing of a cost-effective method is a priority issue in environmental engineering.

2-2-2) Disinfection

Fecal coliform bacteria are a group of bacteria that are passed through the fecal excrement of humans, livestock and wildlife. They aid in the digestion of food. A specific subgroup of this collection is the fecal coliform bacteria, the most common member being *Escherichia coli*.

A large number of pathogens will be destroyed at 55 °C and only a few are able to survive up to 67 °C. To eliminate all pathogen microorganisms, temperatures of 70 °C for

1 to 2 hours is sufficient. For example, the *Salmonella* can be destroyed in 15 to 20 minutes when exposed to a temperature of 60 °C, or in one hour at 55 °C (Carrington, 2001).

Class A biosolids are sewage sludge that has undergone treatment by processes that further reduce pathogen concentrations resulting in an end product that is virtually pathogen-free. These processes include irradiation, composting, heat treatment, pasteurization, and thermophilic aerobic digestion. Class A biosolids do not contain pathogens in sufficient quantity to warrant restricted access or special precautions and may be applied the same way as a commercial fertilizer.

Class B biosolids are sewage sludge that has undergone treatment by processes that significantly reduce pathogen concentrations. These processes include aerobic and anaerobic digestion, air-drying, composting, and lime stabilization. According to the U.S. Environmental Protection Agency (EPA), Class B biosolids may contain pathogens in sufficient quantity to warrant restricted public access and special precautions for exposed workers.

The hazard that is associated with Class B biosolids is a function of the number and type of pathogens in the treated sludge relative to the minimum infective dose and the exposure level. Under the EPA biosolids rule (40 CFR 503), Class B biosolids must contain less than two million colony forming units (CFU) of fecal coliform per gram of total solids (dry weight). To protect public health, the EPA rule prescribes a restricted period of up to one year to limit public access to lands where Class B biosolids have been applied (Lester and Birkett, 1999).

The presence of fecal coliform tends to affect humans more than it does aquatic creatures, though not exclusively. While these bacteria do not directly cause disease, high quantities of fecal coliform bacteria suggest the presence of disease causing agents. If a large number of fecal coliform bacteria (over 200 colonies/100 milliliters (ml) of water sample) are found in water, it is possible that pathogenic (disease- or illness-causing) organisms are also present in the water. Fecal coliform standards are summarized in Table 2-4 (Joklik et al, 1992).

Reduction of fecal coliform in wastewater may require use of chlorine and other disinfectant chemicals. Such materials may kill the fecal coliform and disease bacteria. Fecal coliforms by themselves are usually not pathogenic; they are indicator organisms, which means they may indicate the presence of other pathogenic bacteria. Pathogens are typically present in such small amounts it is impractical to monitor them directly (Tortora et al, 1986).

Table 2-4 Coliform standards (Joklik et al, 1992)

	Colonies / 100 ml
Drinking water	1 TC*
Total body contact (swimming)	200 FC*
Partial body contact (boating)	1000 FC
Treated sewage effluent	Not to exceed 200 FC

**Total coliform (TC)* * *Fecal coliform (FC)*

TC counts are normally about 10 times higher than fecal coliform (FC) counts.

The monitoring procedure in pathogen reduction method is the fecal coliform test (PDEP, 1998). The following methods are some of commonly applied to pathogen reduction in sludge.

2-2-2-1) Heat Treatment

Heat treatment processes are used to stabilize and condition the sewage sludge. The processes involve heating sewage sludge under pressure for a short period of time. The sewage sludge becomes sterilized and bacterial slime layers are solubilized, making it easier to dewater the remaining sewage sludge solids.

In this process, liquid sewage sludge is heated to a temperature of 180°C (356°F) or higher for 30 minutes. Sewage sludge must be properly stored after processing because organic matter has not been reduced and, therefore, regrowth of pathogenic bacteria can occur.

Two processes have been used for heat treatment: the Porteous and the Zimpro processes. The Proteous process requires that the sludge be preheated and then injected into a reactor vessel. Steam is also injected into the vessel under pressure. The sewage sludge is retained in the vessel for approximately 30 minutes after which it is discharged to a decant tank. The resulting sewage sludge can generally be concentrated and dewatered to high solids concentrations.

The Zimpro process is similar to the Porteous process. However, air is injected into the sewage sludge before it enters the reactor and the vessel is then heated by steam to reach the required temperature (PDEP, 1998). Energy consumption in this method is very high. Vapor of mercury during the operation may appear.

2-2-2-2) Thermophilic Aerobic Digestion

In this process, feed sewage sludge is pre-thickened and aerated. In some cases oxygen is injected into the sludge. Because there is less sewage sludge volume and less air to carry away heat (due to thickening), the heat released from biological oxidation warms the sludge in the digester to as high as 60°C (140°F).

Due to the higher temperatures, this process achieves higher rates of organic solids reduction than by conventional aerobic digestion, which operates at ambient air temperature. Biodegradable volatile solids content of the sludge can be reduced by up to 70% in a relatively short time.

Thermophilic aerobic digestion can be accomplished using auxiliary heating of the digestion tanks or through special designs that allow the energy naturally released by the microbial digestion to heat the sludge. Residence time for the thermophilic process is 10 days as opposed to the 40 -60 days for conventional aerobic digestion (PDEP, 1998). This method does not reduce metals in biosolids.

2-2-2-3) Beta Ray Irradiation

Radiation can be used to disinfect sewage sludge. Radiation destroys certain organisms by altering the colloidal nature of the cell contents (protoplasm). Beta rays are electrons accelerated in velocity per electrical potentials in the vicinity of 1 million volts. The effectiveness of beta radiation in reducing pathogens depends on the radiation dose, which is measured in rads. A dose of 1 megarad or more will reduce pathogenic viruses, bacteria, and helminths to below detectable levels.

Sewage sludge must be properly stored after processing because organic matter has not been reduced. Therefore regrowth of pathogenic bacteria can occur. Beta rays have

limited penetration through the sludge. Therefore, beta rays are introduced by passing a thin layer of sludge under the radiation source (PDEP, 1998).

2-2-2-4) Gamma Ray Irradiation

Radiation can be used to disinfect sewage sludge. Radiation destroys certain organisms by altering the colloidal nature of the cell contents (protoplasm). Gamma rays are high-energy photons produced by certain radioactive elements. Gamma rays come from certain isotopes, such as Cobalt 60 and Cesium 137.

Gamma rays can penetrate substantial thickness of sewage sludge and can therefore be introduced to sewage sludge by either piping liquid sewage sludge into a vessel that surrounds the radiation source or by carrying composted or dried sewage sludge by hopper conveyor to the radiation source.

A dose of 1 megarad or more at room temperature will reduce pathogenic viruses, bacteria, and helminths to below detectable levels (PDEP, 1998).

2-2-2-5) Pasteurization

Pasteurization involves heating sewage sludge to above a predetermined temperature for a minimum time period. In detail, the temperature of the sludge is maintained at 70°C (158°F) or higher for 30 minutes.

Sludge can be heated by heat exchangers or by steam injection. The steam injection method is preferred because it is more effective at maintaining even temperatures throughout the sludge batch being processed. Sewage sludge is pasteurized in batches to prevent recontamination that might occur in a continuous process. Sewage sludge must be properly stored after processing because the organic matter has not been stabilized and therefore odors and regrowth of pathogenic bacteria can occur (Metcalf and Eddy, 1991).

2-2-2-6) Conclusion

These disinfection methods are very costly and energy consumption is very high. Most of them need complicated equipment and high levels of professional skill. Therefore, a simple and cost effective method is still required which could be applicable in the WWTP.

2-2-3) Composting

Composting reduces sewage sludge, which has generally been mixed with a bulking agent (i.e. wood chips, bark, sawdust etc.), to a humus-like material through biological degradation. This method can be applied only after dewatering. The bulking agent absorbs moisture, increases porosity and adds a source of carbon to the sludge. Aeration and/or frequent mixing or turning is needed to supply oxygen and remove excess heat. Following this stage, bulking agents may be screened and recycled. The composted sewage sludge is cured for an additional period (PDEP, 1998).

There are three commonly used methods of composting, which are windrow, static aerated pile and within-vessel. Windrow composting involves stacking the sewage sludge/bulking agent mixture into long piles, generally 1 to 2m high and 2 to 5m wide. These rows are regularly turned or mixed using a front-end loader to ensure steady oxygen supply for the microorganisms and to reduce the moisture content. In cold climates, winter weather can significantly increase the amount required to attain temperatures needed for pathogen control.

Static aerated piles use forced-air rather than mechanical mixing to supply oxygen and reduce moisture. The sludge-bulking agent mixture is placed on top of an aeration system such as perforated piping. It is then topped off with a bed of bulking agent. Also,

the entire pile is covered with a layer of cured compost for insulation and odor control. Pumps are used to suck air through the compost pile. The air that is removed from the compost pile, flows into a diffuser or filter pile, which contains the odors given off by the compost pile.

Within-vessel composting takes place in a reactor where the operating conditions can be carefully controlled. The curing period takes place outside of the vessel. Using either the within-vessel, composting method or the static aerated pile composting method, the temperature of the sewage sludge is maintained at 55°C (131°F) or higher for 3 days. Using the windrow method, the temperature of the sewage sludge is maintained at 55°C (131°F) or higher for 15 days or longer. During the period when the compost is maintained at 55°C (131°F) there shall be a minimum of five turnings of the windrow.

In general, within-vessel composting attains the required conditions in approximately 10 days. The static-pile and windrow processes generally require about 3 weeks. Longer composting periods may be necessary to fully stabilize the sludge. If volatile solids remain in the sludge, fecal coliform can later regrow to significant numbers (PDEP, 1998).

2-2-4) Biosolids Disposal

Dewatered biosolids is often buried in a sanitary landfill. Regulation in some countries does not permit disposal on sanitary landfill. Some countries eliminated the landfill system (e.g. France). Some biosolids (e.g. activated sludge) are useful as fertilizer or as soil conditioner if properly mixed with the surface soil. Soil microbes will assist in further stabilization of any biodegradable organics remaining. Land spreading of biosolids is very popular too. However, concentration of heavy metals must be controlled

and also monitoring of the heavy metal concentrations in the environment is needed. More attention is necessary to potentially toxic metals. Mixture of biosolids and incinerated fly can be used as road bed or construction material if appropriate care is taken (Carberry et al, 1983).

According to the Canadian Council of Ministers of the Environment (CCME), fecal coliforms must be less than 1000 most probable number (MPN) / g of total solids calculated on a dry weight basis. The concentration of trace metals in the soil shall not exceed those levels provided in Table 2-5 (CCME, 1996) as calculated on a dry weight basis.

Table 2-5 Concentration of trace elements in soil (CCME, 1996)

Metals	Category A* (mg/kg dry weight)	Category B** (mg/kg dry weight)
As	13	75
Cd	3	20
Co	34	150
Cr	210	1060
Cu	100	757
Hg	0.8	5
Mo	5	20
Ni	62	180
Pb	150	500
Se	2	14
Zn	500	1850

*Category A: This concentration can be used in any application such as agricultural lands, residential gardens, the nursery industry, and other businesses.

** Category B: This concentration has a restricted use.

Finally a safe disposal of biosolids requires an extensive dewatering, absence of heavy metals and pathogens. At the present time, different technologies are applied for each of the above-mentioned objectives if any. A new restriction for run off waters, due to lethal accident in Walkerton, Ontario, requires more limited methods of biosolids disposal. Therefore, a new technology, which will be able to cover all the above-mentioned objectives, is required. Based on previous investigations by Elektorowicz et al (1996-1999) at Concordia University, it was assumed that electrokinetic method might fulfill all objectives.

2-3) Electrokinetic Method

2-3-1) Introduction

The Electrokinetic Phenomena (EK) can be used for removing water, metals and organic contaminants. Electrokinetic processes take place when a DC current is supplied to soil, mud, and sludge. They are capable of desorbing, and removing metals and polar organics. This *in-situ* technology was primarily used for soil consolidation. Recently, some researchers have used it for contaminant removal.

The principle of electrokinetic remediation relies upon application of a low-intensity direct current through the soil between electrodes (cathode and anode) (Elektorowicz, 1995). This mobilizes charged species, causing ions and water to move toward the electrodes. Metal ions, ammonium ions, and positively charged organic compounds move toward the cathode. Anions such as chloride, cyanide, fluoride, nitrate, and negatively charged organic compounds move toward the anode (Choudhury, 1998). The current creates an acid front at the anode and a base front at the cathode (Hakimpour, 2001). This generation of acidic condition helps to mobilize sorbed metal contaminants

for transport to the collection system at the cathode. A typical diagram of the electrokinetic process is shown in Figure 2-11 (Choudhury, 1998).

Targeted contaminants for electrokinetic are heavy metals, anions, and polar organics in soil, mud, and sludge. Concentrations that can be treated range from a few parts per million (ppm) to tens of thousands ppm. Electrokinetic is most applicable for a high colloid content medium (e.g. clayey soil).

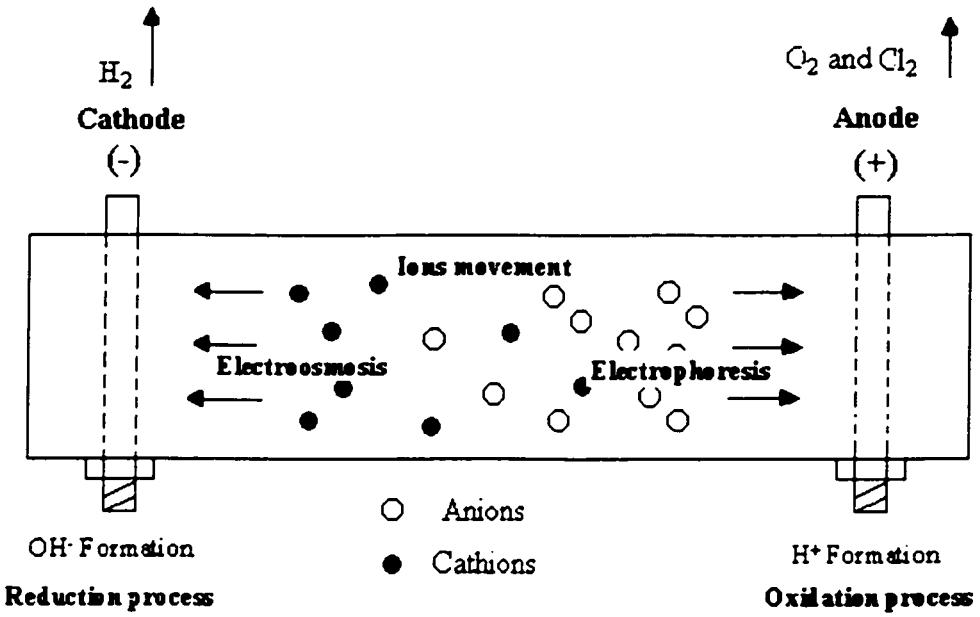


Figure 2-11 A typical electrokinetic process

2-3-2) Electrokinetic Phenomena

The two principal electrokinetic processes of interest are electrophoresis (motion of a particle in an electric field) and electroosmosis (the induction of flow at a charged surface by an electric field, the opposite of electrophoresis). Table 2-6 summarizes these phenomena (Brett & Brett, 1993).

These phenomena are reflections of the interaction of dissolved charges (ions) with a surface carrying a fixed surface charge density leading to a zeta (or electrokinetic) potential at the plane of hydrodynamic shear.

Table 2-6 Principal electrokinetic processes (Brett & Brett, 1993)

Phenomena	**Stationary phase**	**Mobile phase**	**What causes the movement**
Electroosmosis	Solid	Liquid	Applied electric field
Electrophoresis	Liquid	Solid	Applied electric field

2-3-2-1) Electroosmosis

Movement of liquid in a solids phase due to the application of an electric field is called electroosmosis (EO). The most widely accepted theory for this phenomena is that water surrounding the ions is dragged along via friction forces during movement of cations to the cathode and anions to the anode (Eykholt & Daniel, 1994). For a negatively charged particle, a relatively immobile layer of cations will be held in the Stern layer, while in the diffuse layer, cations and some anions will be found as well as water molecules. In the bulk solution, the associated cation and anion charges will be balanced more cations than anions are in the diffused double layer (Figure 2-12), a net flow of water toward the cathode will occur.

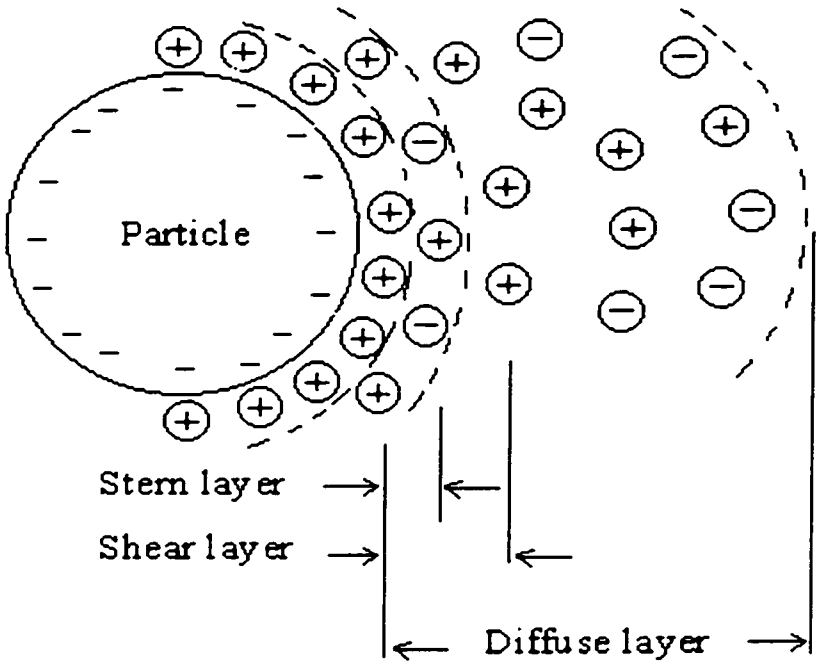


Figure 2-12 Double layer charge distribution (Judith et al, 1983)

The driving force caused by electroosmotic flow is indicated by the coefficient of electroosmotic permeability (K_E), which is defined as the volume rate of water flowing through a unit cross-sectional area due to unit electric gradient under constant conditions and for a short duration of testing. The electroosmotic flow rate is estimated using the following equation (Schaad et al, 1947):

$$Q = K_E \cdot E \cdot A \qquad (2.1)$$

Where:

Q = EO flow rate (cm^3/s)

K_E = coefficient of EO permeability ($cm^2/V.s$)

E = potential gradient (V/cm)

A = cross-sectional area (cm^2)

The value of K_E is a function of zeta potential, viscosity of the pore fluid, size of pores, and electrical permeability of the soil medium. It is hypothesized that the drop in pH of the soil due to electrokinetic processing will cause a decrease in the coefficient of electroosmotic permeability associated with the drop in zeta potential (Choudhury, 1998).

2-3-2-2) Electrophoresis

Movement of solids in a liquid phase due to the application of an electric field is called electrophoresis (Mitchell, 1976). This definition includes all electrically charged particles such as colloids, clay particles in pore solution, organic particles and droplets. The following forces are acting on the particles (Brett & Brett, 1993):

- Forces of the electric field on the particle
- Frictional forces
- Forces due to the action of the electric field on ions of the opposites charge to the particle within the double layer
- Induction forces in the double layer caused by the electric field

2-3-2-3) Electrolyte migration

With the application of direct current, water present at the electrodes will undergo electrolysis and dissociation into H^+ (oxidation) and OH^- (reduction) take place. Due to oxidation-reduction processes, pH decreases at the anode area and increases at the cathode area (Elektorowicz et al, 1995; Elektorowicz & Hatem, 1999). These reactions are shown in the following equations:

Oxidation in anode: $2\,H_2O \longrightarrow O_{2\,(gas)} + 4H^+ + 4e^-$ (2.2)

Reduction in cathode: $2\,H_2O + 2\,e^- \longrightarrow H_{2\,(gas)} + 2\,OH^-$ (2.3)

Electrolyte migration is the migration of ionic species present in the pore fluid as well as the migration of H^+ (produced at the anode) and OH^- (produced at the cathode) toward the opposite electrode (Pamukcu, 1992). In theory, as the cations migrate toward the cathode, they can drag a significant quantity of water molecules. Migration of the hydrogen and hydroxyl ions under the action of electric field causes acidic condition near the anode and alkaline conditions near the cathode.

2-3-3) Application of Electrokinetic Phenomena

2-3-3-1) Heavy metal removal

The significant transport mechanism of heavy metals is electrolyte migration so they must be in ionic form in the liquid to be transported to the cathode in the electrokinetic processes. In order to maintain electroneutrality, OH^- ions are produced at the cathode constantly. The ion production increases the pH value at the cathode. These ions migrate to the anode at a rate of their ionic mobility. High pH development in the cathode region creates a precipitation barrier that decreases heavy metal removal.

The research of Elektorowicz (1995) regarding to the technical requirements related to electrokinetic removal of contaminants from soil shows that one of the major factors is lowering pH in cathode region. This allows mobilization and accessibility of heavy metals to electrokinetic transport.

2-3-3-2) Dewatering

The electroosmotic was used for dewatering of clayey thixotropic soils since 1930 (Casagrande, 1948). Dewatering of biosolids based on the electroosmosis phenomena is not developed yet due to the complex medium of the biosolids. However, this innovative technique can be remarkably effective for difficult to dewater sludge such as very fine

particles and gelatinous materials. Some lab scale research has been initiated. Gazbar (1995) designed a laboratory cylindrical cell to investigate the combined action of electroosmotic drainage and mechanical compression on sludge dewatering.

The experimental procedure consisted of compressing the sludge for 2 hours under 4 kg/cm^2. The cakes are then subjected for 1 hour to a pressure of 40 kg/cm^2 without an electrical field and to the same pressure (4 kg/cm^2) with an electrical field of 15 V/cm. Generally, the dewatering is not improved considerably by increasing the pressure from 4 to 40 kg/cm^2. However, the application of an electrical field under the same pressure shows a substantial increase in sludge solid concentrations from the initial value of 42.2% to 50.9%.

Banerjee and Law (1997) also prepared a cylindrical cell to investigate the dewatering at both constant voltage and constant current of two biomass materials including organic humus with peat and composted wastewater sludge. Results showed that the moisture content of humus decreased to 22.5% from an initial value of 44.3% (volumetric wet basis) after 2 h 10 min of electroosmosis at a potential of 50V across a 2.9 cm thick bed. They found out that rate of catholyte at constant voltage linearly increased with time in the applied electric field.

2-3-4) Conclusion and Research Objectives

The application of electrokinetic for biosolids management is a new approach that needs more research. The only goal of previous research was the reduction of water content in biosolids, however, this method is able to improve the quality of biosolids and consequently it has more options to revitalize biosolids.

This research focuses on the reduction of the water content, heavy metals, organic content, and pathogens using electrokinetic phenomena. Investigation of a new methodology will consider the use of simple solutions with no expensive materials to develop a cost-effective technology.

Chapter 3

Experimental Methodology

As mentioned in the previous chapter the fulfilled of the research objectives will be accomplished by investigation of the use of electrokinetic phenomena due to the development of a new technology for biosolids management.

The description of the experimental set up and the analytical methods used in this experiment for obtaining data and results are explained in this chapter. Figure 3-1 summarizes the methodology that was applied in the experiment.

3-1) Initial Biosolids Sampling

Biosolids were obtained from the Auteuil Wastewater Treatment Plant containing a secondary treatment unit, which is located in Laval, Quebec (Figure 3-2). Generally, the plant has the following management of biosolids. After the removal of large particles, sludge enters into the primary treatment unit for removal of the floating and settleable solids. The top effluent of this unit is the influent of the secondary treatment unit, which is applying the attached growth method. In the secondary treatment, biological and chemical processes are used for removing most of the organic matter. Finally, biosolids are transferred to the incineration unit. Biosolids for our research purposes were sampled at the point situated before the dewatering unit and after the adding of polymer (as shown in Figure 3-2). The biosolids were collected in two 20 L plastic containers and kept at 4 °C.

3-1-1) Initial Characterization of Biosolids

Table 3-1 contains some characterizations of the initial sample that was taken from the wastewater treatment plant.

Table 3-1 Characterizations of initial biosolids

Solids content	3.4 %	
Organic content	62 %	
pH	5.37	
Sulfate (SO_4^{2-}) mg / kg dry solid	163	
Chloride (Cl^-) mg / kg dry solid	9 004	
Pathogen	Positive	
Metal content mg / kg dry solid	Lead	37
	Cadmium	0.2
	Copper	310
	Zinc	685
	Nickel	105
	Iron	21 920

3-2) Set-up of Experiment Installation

The experiment was performed in 6 cells. All cells were made from rigid polyethylene and they had same dimensions of length = 22.0 cm, width = 5.0 cm, and depth = 5.2 cm. Based on previous experiments [Elektrowicz (1995), Elektrowicz (1996b)], a perforated stainless steel tube was used as cathode and anode. The outer and inner diameter of this tube was 1.0 cm and 0.6 cm respectively. The center to center distance between the cathode and the anode was 18 cm in all cells. The bottom of the anode was closed and sealed against any leakage. A plastic vial (50 mL) was connected to the bottom of the cathode for collection of the catholyte. For monitoring the electrical parameters, silver probe electrodes were used. The diameter of these probes was 0.10 cm and the distance between probes was 1.50 cm.

Eleven probe electrodes were inserted into the biosolids between the cathode and the anode. The distance between the bottom of the cells and the probes was 0.5 cm.

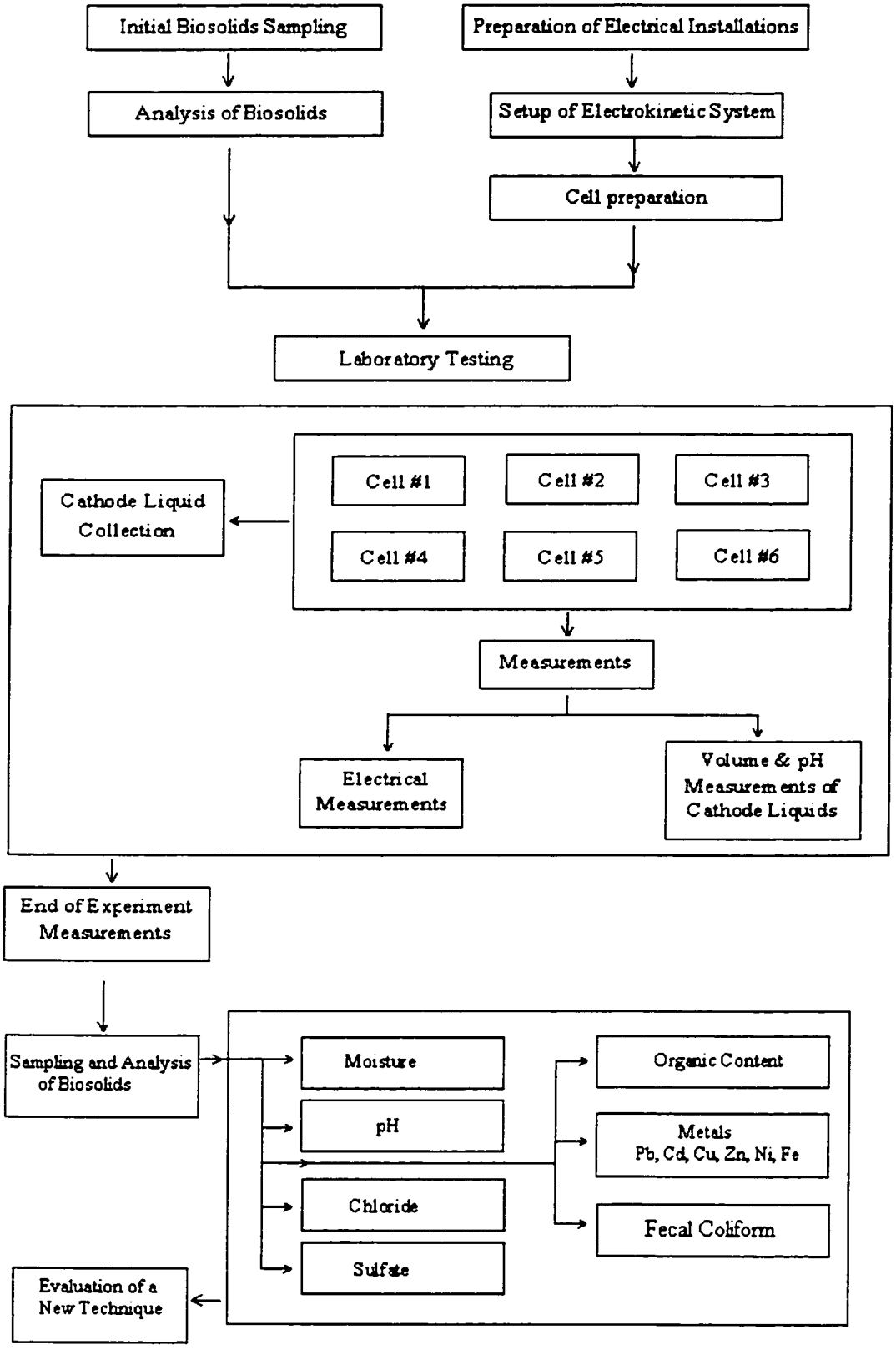
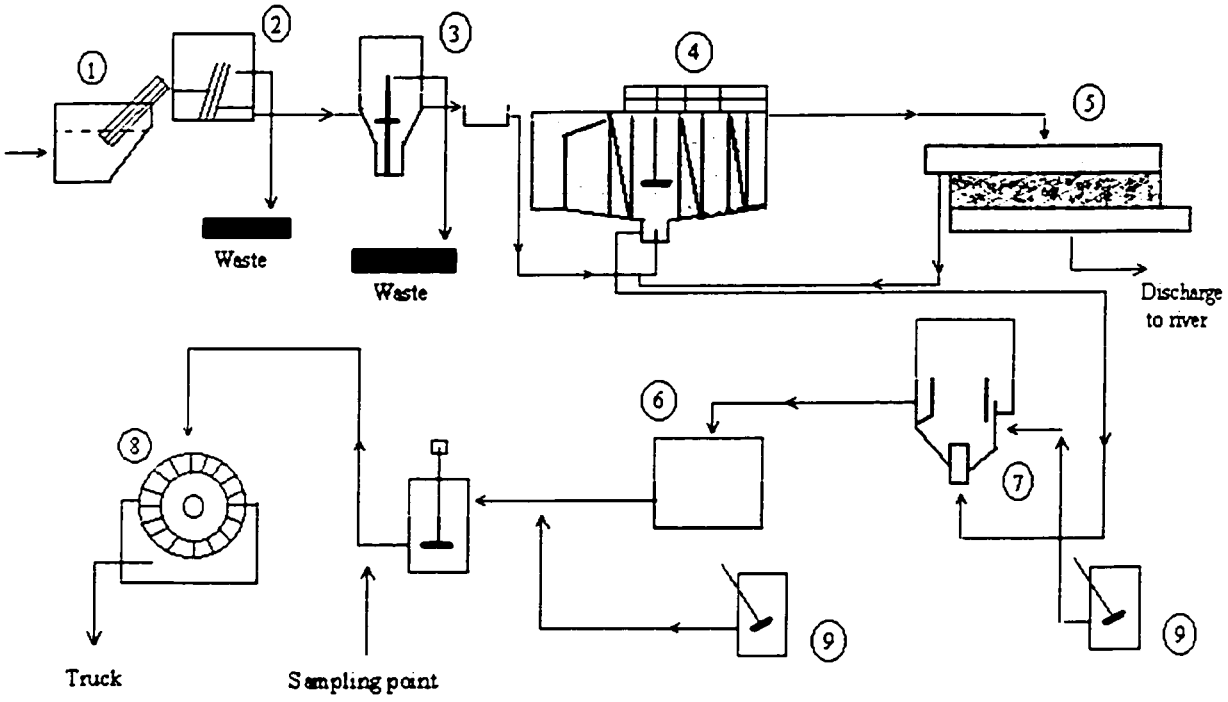


Figure 3-1 Methodology of the experiments



1- Influent
2- Physical separation
3- Decanter
4- Primary treatment
5- Secondary treatment
6- Storage
7- Thickening
8- Dewatering
9- Polymer preparation

Figure 3-2 Scheme of Wastewater Treatment Plant in Laval (Quebec)

The distribution of the voltage gradient between the cathode and the anode was monitored by direct measurements of the potential between electrodes and probe electrodes. This measurement was carried out every 24 hours. Figure 3-3 shows the cell configuration in the experiment.

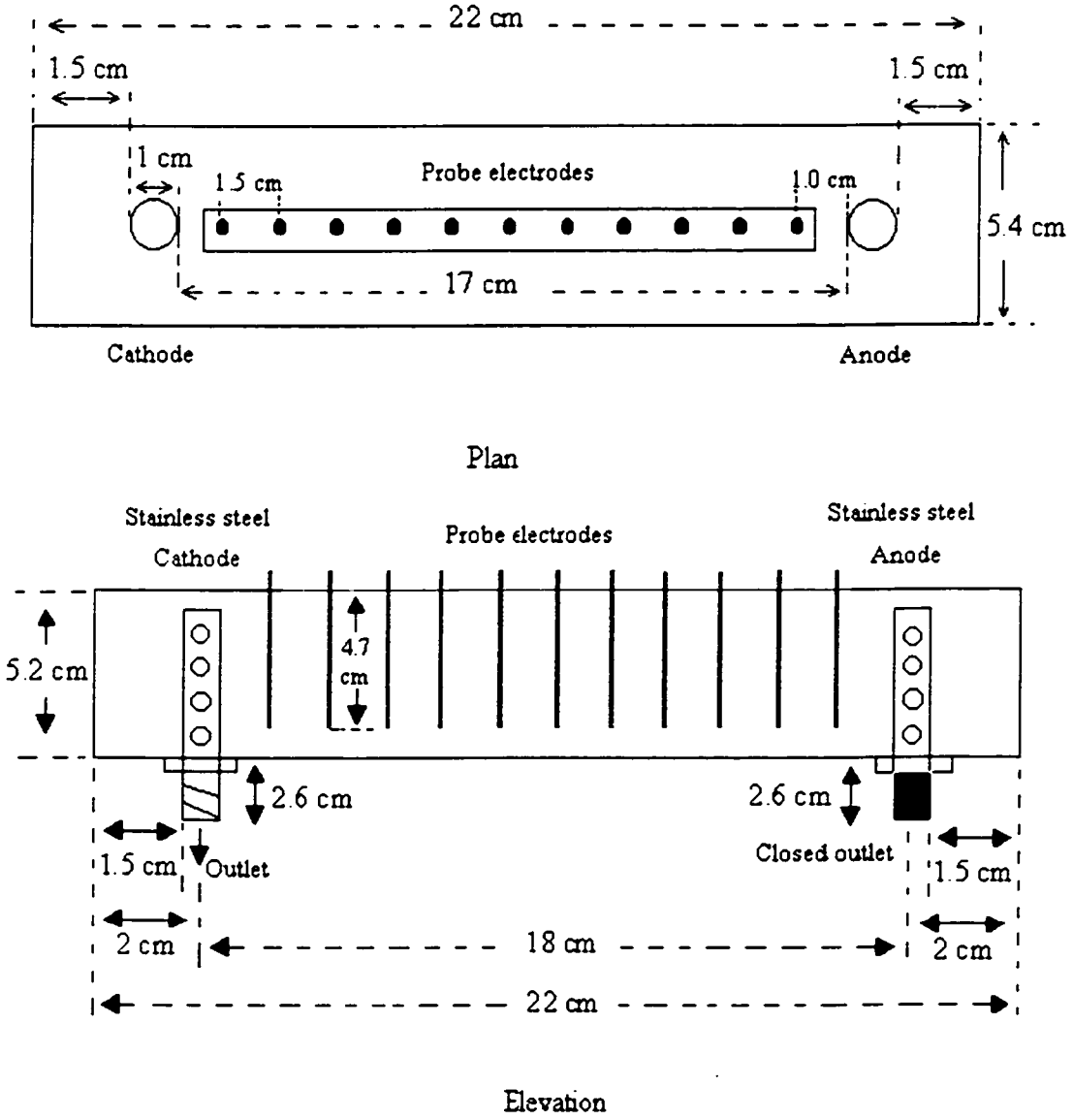


Figure 3-3 Cell configuration in the experiment

3-3) Apparatus, Reagent and Equipment

This section contains a summary of the significant apparatus and equipment that were used in the experiment.

3-3-1) Cell Construction

Apparatus and equipment

- 6 polyethylene containers
- 12 stainless steel electrodes (D_{out} = 1.0 cm, D_{in} = 0.6 cm) covered with stainless steel mesh (200)
- 66 silver probe electrodes (D = 1.0 cm)
- 50 mL plastic bottles
- DC power supply (2 units)
- Digital multimeter (Mastercraft)
- Balance (Mettel Toledo, PB 1502-5)
- Electrical control table

Reagent

- Di ammonium phosphate (Commercial fertilizer)

3-3-2) Measurements and Analysis

Apparatus and equipment

- Mechanical shaker (Aros 160)
- pH meter (Fisher Scientific, AR 25)
- Atomic absorption spectrometer (Perkin Elmer, Analyst 100)
- Turbidity meter model 2008 (La MOTTE)
- Microscope (Micro Master)

- Thermometer
- Petri dishes
- Sterilized membrane filter (0.45 μm)
- 20 mL plastic vials
- 20 mL sterilized glass vials
- Plastic foil and plastic bags
- Ceramic containers
- Water bath (Blue M)
- Pipettes (1 mL, 10 mL, and 20 mL)

Reagents

- Distilled water
- Buffer solutions (pH = 4, pH = 7, pH = 10)
- HCl (4 M)
- Potassium chromate (K_2CrO_4)
- Barium chloride
- Buffer solution A (30g magnesium chloride, 5 g sodium acetate, 1.0g potassium nitrate, and 20 mL acetic acid in 500 mL distilled water and make up to 1000 mL)
- NaOH solution (1 N)
- Silver nitrate ($AgNO_3$) solution
- NaCl Standard solution
- M-FC agar

3-4) Test Preparation

In this experiment, 6 cells were prepared to study the dewatering of biosolids in different electrokinetic conditions. The volume of 900 mL of well-mixed biosolids from WWTP was poured in each cell. During this operation, the excess water was drained from cathode to the plastic bottles. The volume of collected water was about 450 mL in each cell. To prevent blocking of the drainage system of the electrodes, a stainless steel mesh (200) was used to cover the electrodes. This cover also prevents the passing of fine particles with the water through the cathode.

Alkalinization of sludge reduces the viability of ascaris eggs (Ghiglietti et al, 1997). Therefore, di-ammonium- phosphate (fertilizer) was added to cell #1 and cell #2. Considering the purity of fertilizer and the percentage of ammonia (20% NH_4 in fertilizer), 43 g of fertilizer was dissolved in 150 ml distilled water and added to the mentioned cells. Table 3-2 summarizes the condition of each cell in detail.

Table 3-2 Cells condition in the experiment

Cell No.	Voltage gradient (V/cm)	Fertilizer added	Symbol
1	0.5	Yes	N-E(0.5)
2	1.5	Yes	N-E(1.5)
3	0.0 (Control cell)	No	E(0)
4	0.5	No	E(0.5)
5	1.0	No	E(1.0)
6	1.5	No	E(1.5)

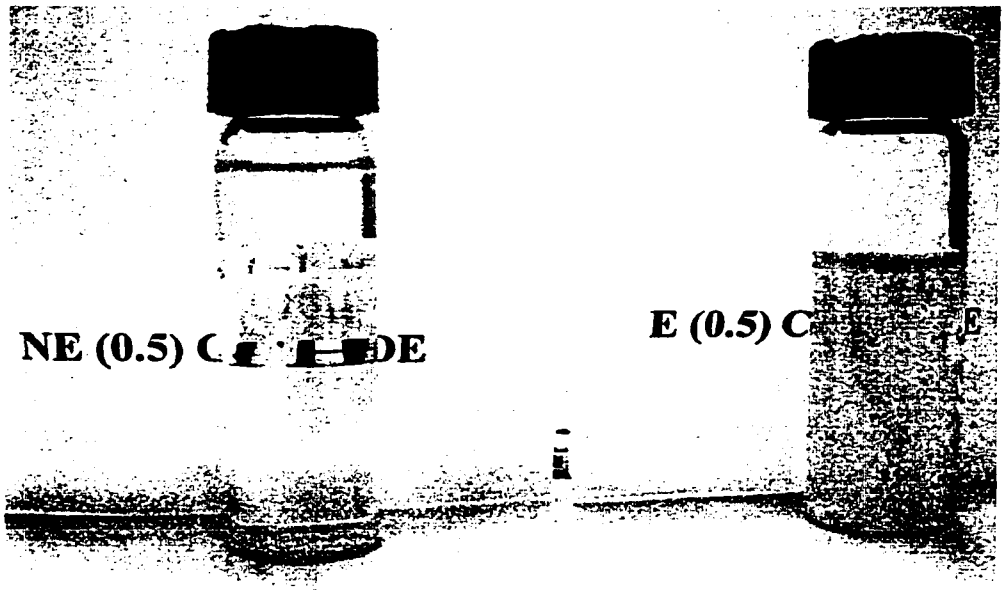
After pouring biosolids and fertilizer (cells #1 and #2), probe electrodes were inserted into the biosolids and the cover of the cells was placed on top. The DC power supply was connected to the cells and the desirable voltages were set up at 0.5 V/cm, 1.0 V/cm, and 1.5 V/cm in respective cells.

3-5) Observations during the Experiments

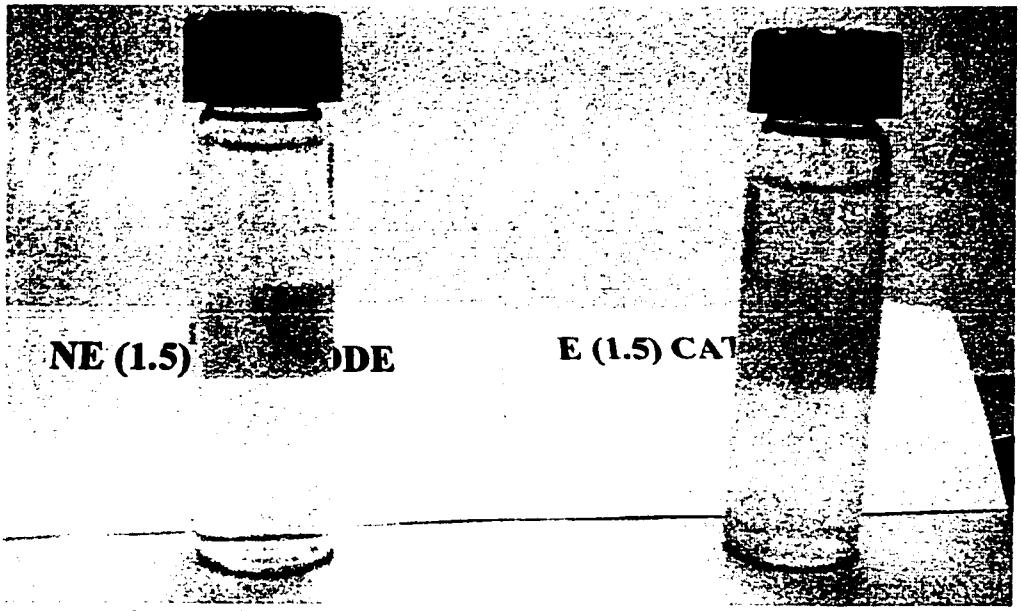
Cells #3 [E (0)], #4 [E (0.5)], #5 [E (1.0)], and #6 [E (1.5)] were prepared on the first day of experiment and connected to the DC power supply. Preparation and connection to the electrical system for cells #1 [N-E (0.5)] and #2 [N-E (1.5)] was carried out on the second day.

The catholyte of each cell was transferred to 20 mL sterilized glass vials every day. The liquids that were collected from the cathodes of cells #1 [N-E (0.5)] and #2 [N-E (1.5)] were clear but the collected liquids from other cells were yellowish. As shown in Figure 3-4, the catholyte of cell #2 [N-E (1.5)] is clearer than the catholyte of cell #1 [N-E (0.5)] and also the catholyte of cell #6 [E (1.5)] is clearer than the catholyte of cell #4 [E (0.5)]. Therefore, higher voltage increases this clearness.

The pH value and the volume of catholyte collected from each cell were measured on a daily basis. The condensed water under the cover of cells #4 [E (0.5)], #5 [E (1.0)], and #6 [E (1.5)] was observed around the cathode on the second day. The volume of the catholyte in cell #5 [E (1)] was more than cells #4 [E (0.5)] and #6 [E (1.5)]. The volume of collected water in cell #6 [E (1.5)] was more than that in cell #4 [E (0.5)].



(a) Clear liquid in NE (0.5) and yellowish liquid in E (0.5)



(b) Clear liquid in NE (1.5) and yellowish liquid in E (1.5)

Figure 3-4 Comparison of catholyte quality in cells with and without fertilizer

On the 3rd day, the volume of the catholyte was reduced dramatically in cells #3 [E (0)], #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] but it was quite high in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] (the second day for these two cells). The condensed water still remained under the cover of cells #4 and #5.

On the 4th day of the experiment, liquid extraction from the cathodes of all cells was stopped except in cell #1. On that day, a hole in the biosolids was observed around the anode in cell #2 [N-E (1.5)]. This could be as a result of electrophoretic movement of particles to the cathode. The condensed water under the cover of cells #4 [E (0.5)] and #5 [E (1)] was also seen on the 4th and 5th days. On the 5th day, the hole around the anode in cell #2 was developed and the same condition began to develop around the anode in the cell #1 [N-E (0.5)].

On the 6th day of the experiment no water discharged through the cathode and the electrical power was disconnected for 24 hours. The electrical power was reconnected on the 7th day. The volume of 0.5 mL of water was collected from cell #1 on the 8th day but no water was observed in the other cells. The size of holes in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] increased every day. The hole in cell #2 was bigger than the hole in cell #1 demonstrating proportionally higher electrophoretic movement in cell with higher potential. Volume reduction of biosolids in cells #1 [N-E (0.5)], #2 [N-E (1.5)], and #6 [E (1.5)] was quite obvious.

The pH value of the catholyte was measured in all cells every day. Except for the control cell, the pH of the catholyte in all cells was found to be in the alkalinity range. Therefore, it could be concluded that the pH value of the catholyte had increased due to the electrokinetic phenomenon and the effect of the fertilizer was negligible. The

experiment ended on the 10^{th} day and the electrical power was disconnected. Subsequently all cells were emptied and subjected to the sampling procedure.

No corrosion was observed in the cathodes and anodes except the anode in cell #6 [E (1.5)]. It was broken in two parts from the connection point to the bottom of the cell. The stainless steel covering mesh on the cathodes had a little corrosion but its corrosion was observed mostly in the anodes. Comparing cells #2 [N-E (1.5)] and #6 [E (1.5)] showed that the fertilizer in cell #2 [N-E (1.5)] prevented from corrosion remarkably. This information is important for designers to save equipment and reduce maintenance costs.

3-6) Measurements during the Experiments

The voltage along the distance between the cathode and the anode was monitored during the experiment on a daily basis. Each reading represents a voltage gradient between the cathode and the subsequent probe electrode. The total current of each cell was also measured daily.

The temperature of all cells was measured during the experiment. The temperature of all cells was read around 24 °C every day but it was around 23 °C for the control cell. The volume and the pH value of the catholyte were also measured every day.

3-7) Biosolids Sampling Procedure

After disconnection of DC current, biosolids were sampled at known distances. Figure 3-6 shows the sampling procedure. The samples that were taken 0.5 cm away from the cathode and anode were named C and A respectively. BC and BA represented the samples from back cathode and back anode. The rest of the distance between the

cathode and the anode (16.0 cm) was divided into 16 equal samples (1.0 cm thickness for each sample). These samples were named 1 to 16 starting from the cathode side.

The width of each sample was 5.4 cm. As shown in Figure 3-7, the samples were divided into three parts including left side (1.5 cm width), right side (1.5 cm width), and middle (2.4 cm width).

Each sample was separately wrapped in plastic foil and the samples of each cell were put in a plastic bag. All of them were kept at 4 °C.

The middle portions were used for measurement of moisture content, inorganic content, and metal content. The left and right portions were used for analysis of pH, sulfate, chloride and fecal coliforms.

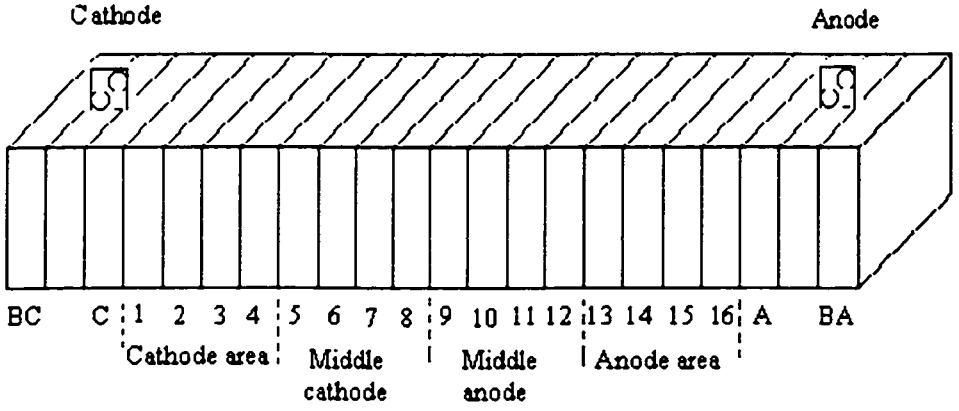


Figure 3-5 Scheme of sampling procedure

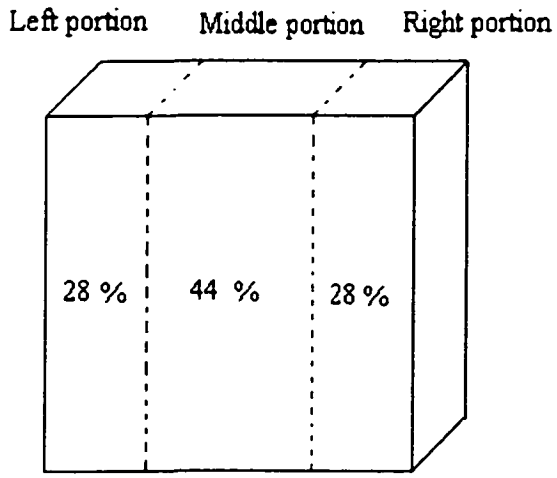


Figure 3-6 Partitioning of each slice

3-8) Measurements and Analysis after the Experiments

3-8-1) Moisture Content

To determine the moisture content the method ASTM 2216-90 (vol. 4.08) was used. Biosolids samples (middle portions) were dried in an oven at 105 °C for 24 hours. Then samples were placed in a decicator for 15 minutes. The samples were weighed and water content was calculated using the following equation:

$$\text{Water content } \% = [(M_{wet} - M_{dry}) \times 100] / M_{wet} \quad (3.1)$$

Where:

M_{dry} = mass of dry biosolids

M_{wet} = mass of wet biosolids

3-8-2) Organic Matter Measurement

This analysis was performed based on test method 2540-E (Clesceri et al, 1989). All samples were dried at 105 °C, weighed and placed in a furnace at 550 °C for 2 hours.

The remaining solids represent the fixed total, dissolved, or suspended solids while the weight lost is the volatile solids. This determination offers a rough approximation of the amount of organic matter that is present in the biosolids.

The organic matter content of the weighed samples was calculated by the following equation:

$$\text{Organic matter content \%} = [(M_{105} - M_{550}) \times 100] / M_{105} \qquad (3.2)$$

Where:

M_{105} = mass of sample after 105 °C

M_{550} = mass of sample after 550 °C

3-8-3) pH Measurement

Each cell was divided into four sections (as shown in Figure 3-5) including cathode area, middle cathode, middle anode, and anode area. The amounts of 5 g of biosolids and 20 mL of distilled water were shaken for 24 hours by the mechanical shaker in 50 mL bottles laying down. The speed of the shaker was maintained at120 RPM. The pH value and the temperature of samples were measured by the digital pH meter (Fisher, AR 25).

Then, all samples were centrifuged (3000 RPM for 10 minutes), filtered (Fisher, paper filter 41) and preserved for analysis of chloride and sulfate.

3-8-4) Chloride (Cl^-) Measurement

The chloride analysis was carried out based on the test method 4500-Cl^- -B (Clesceri et al, 1989). The pH value of all samples was measured and adjusted to between 7 to 10 using NaOH solution (1 N). Then depending on the volume of the sample, an indicator of potassium chromate (K_2CrO_4) was added with ratio of 0.1 mL of indicator to 10 mL of sample.

Titration of samples was done by a standard solution of silver nitrate (2.395 g $AgNO_3$ in 1000 mL distilled water) until the samples turned to pinkish yellow.

To find out the normality of the silver nitrate ($AgNO_3$) solution, titration was carried out by a NaCl solution (0.0141 N). Results showed that the normality of the $AgNO_3$ solution was the same as the NaCl solution so there was no correction factor needed (B = 0).

The concentration of chloride was calculated by using the following equation:

$$\text{Chloride content (mg } Cl^- \text{/L)} = (A-B)x\ N\ x\ 35450 / \text{mL sample} \qquad (3.3)$$

Where:

A = mL titration for sample

B = mL titration for for blank, and

N = normality of $AgNO_3$

3-8-5) Sulfate (SO_4^{2-}) Measurement

The test method 4500-SO_4^{2-} -E (Clesceri et al, 1989) was used to analyze sulfate in samples. The Turbidity meter model 2008 (La MOTTE) was used for measuring turbidity. To draw a standard cure, solutions of 0.1 mg (SO_4^{2-}) / L, 0.2 mg (SO_4^{2-}) /L, 0.4 mg (SO_4^{2-}) /L, 0.5 mg (SO_4^{2-}) /L, and 1.0 mg (SO_4^{2-}) /L were prepared by using $MgSO_4$. The volume of 3.0 mL of buffer solution A (30g Magnesium chloride, 5 g sodium acetate, 1.0g potassium nitrate, and 20 mL acetic acid in 500 mL distilled water and make up to 1000 mL) was added to 15 mL of each sample as well as standard solutions. The turbidity of the samples was measured before and after adding 0.03 g barium chloride

($BaCl_2$). The difference between these two turbidities indicates the concentration of SO_4^{2-} in the solution.

3-8-6) Metal Content Measurement

The metal concentration in biosolids for this test was measured by the following steps. The extraction of metals from the samples was done based on test method 2540-E (Clesceri et al. 1989). All samples were dried at 105 C overnight and were placed at 550 °C for 2 hours to remove the organic matter. Dry samples were crushed in 50 mL plastic vials. HCl (4M) was added to the vials, with a ratio of 25 mL of acid per 5 g of dry sample.

These suspensions were shaken for 24 hours. The samples were filtered and the metal content test was performed using an Atomic Absorption Spectrometer (Perkin Elmer, Analyst 100). The analysis was performed for nickel, zinc, copper, lead, cadmium, and iron.

3-8-7) Fecal Coliform Test

Test method 9222-D (Clesceri et al. 1989) was applied for analysis of fecal coliform as an indicator of pathogen existence in the biosolids. The amount of 0.8 g sodium hydroxide and 1.0 g rosolic acid were added to 100 mL distilled water and shaken for 10 minutes (solution D). Then the amount of 5.2 g M-FC agar was added to 100 mL distilled water and heated. After boiling for 1 minute, 1 mL of solution D was added and shaken. A volume of 5 mL of this solution was poured into each petri dish.

Distilled water was added to 1 g of biosolids samples. The amount of water added was related to the dewatering ratio during the experiment. Then a solution of 1:100 of each sample was prepared. A volume of 20 mL of these solutions was taken in a 20 mL

plastic vial for this test. Sterilized membrane filters (0.45 μm) were used for filtering of the samples by a mechanical filter. Contaminated filters were placed in the petri dishes that were prepared previously.

All plates were transferred into plastic bags and were submerged in a water bath at a fixed temperature of 44.5 °C. After 24 hours, the plates were taken out of the water bath and colonies produced by fecal coliform (various shades of blue) on the filters were counted.

3-8-8) Electrical Parameters

The electrical current (I) of each cell and the potential (V) at each probe electrode were measured daily using Digital multimeter (Mastercraft). By using the following equation, the resistance and its variation with the distance from the cathode were calculated.

$$R = V/I \tag{3.4}$$

Where:

R = resistance (Ohm)

V = electrical potential (V)

I = electrical current (A)

Chapter 4

Results and Discussion

As mentioned in the previous chapter, 6 cells were set up for this experiment. This chapter shows results of measurements and analysis, which are performed during the experiment.

4-1) Solids Content

Moisture content in each sample was measured and then solids content was calculated. Figure 4-1 illustrates the solids content in all cells. Obviously, the solids content in the initial sample is less than all other cells. The curve of the control cell shows the effect of the drainage system (without electrical current). In cell #1 [N-E (0.5)], the solids content was increased from cathode to the middle of the cell gradually. The rate of solids content was increased from the middle area to the anode area very fast.

In cell #2 [N-E (1.5)], the solids content increased from cathode to the middle anode area slowly. This rate was dramatically high from the middle anode to the back anode. The highest and lowest amount of solids content was 61.65% and 17.9%, respectively. The maximum and minimum solids content in cell #1[N-E (0.5)] were 41.94% and 13.83% respectively.

Cell #3 [E (0)] as a control cell was not connected to the DC power supply. Moisture reduction in this cell was only due to the drainage system through the cathode. Solids content was almost the same between the cathode and the anode (11 %).

The solids content in cells #4 [E (0.5)] and #5 [E (1.0)] was 12% and 15% respectively, which was very close to the control cell. The variation of solids content between the back cathode and the back anode in cells #4 [E (0.5)] and #5 [E (1)] were

below 0.5% respectively. Cell #6 [E (1.5)], which has higher electrical potential, had higher solids content compared to cells #4 [E (0.5)] and #5 [E (1)]. The maximum solids content in this cell was 21%.

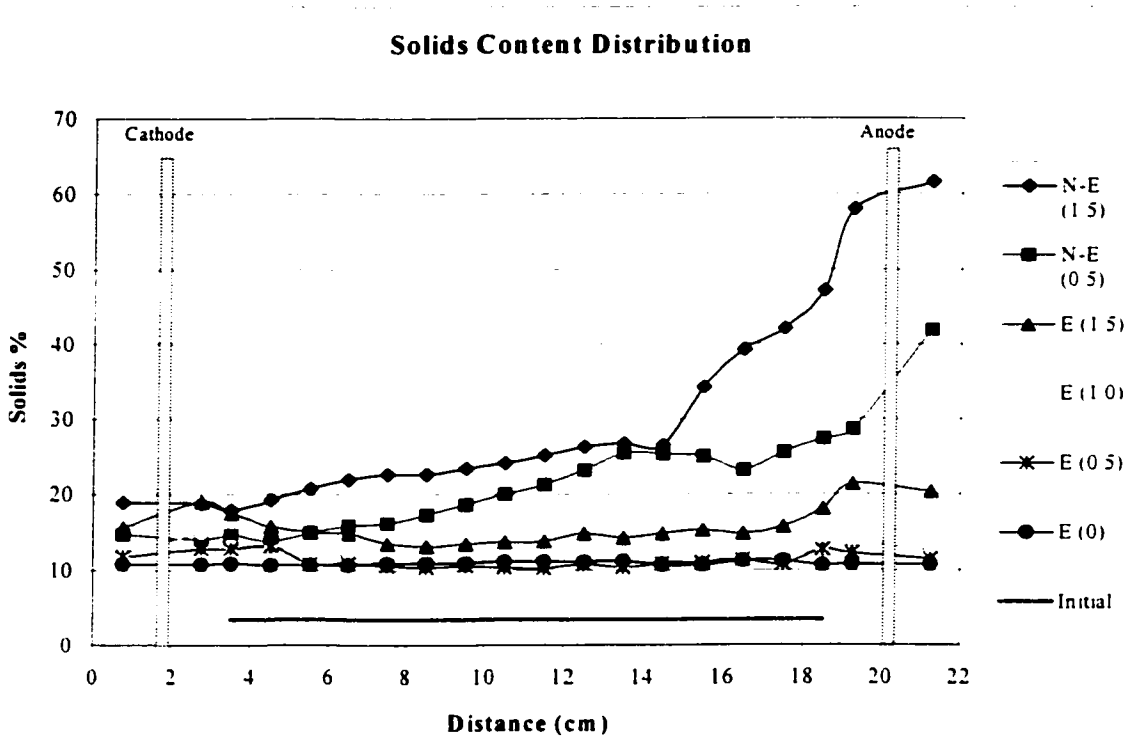


Figure 4 –1 Solids content distribution in all cells

Comparison of the solids content between cells #1 and #2 (with fertilizer) and other cells shows that the electrokinetic process with fertilizer had very high efficiency in biosolids dewatering especially in the anode area. The increase of voltage did not have much effect on water removal.

The average solids content in cells with fertilizer was 48% higher than cells without fertilizer. The highest amount of solids content, which was 61.65%, was observed in the anode area of the cell with fertilizer and voltage of 1.5 volt per cm. This amount is 95% higher than the solids content of the initial sample. The average solids content in cells with a higher voltage (1.5 V/cm) is 28% higher than cells with a lower voltage (0.5

V/cm). The cell with fertilizer and 1.5 V/cm has an 89% higher average solids content compared to the initial sample.

Figure 4-2 shows the average solids content in all cells. Cell #2 [N-E (1.5)] had the highest amount of solids content with a huge difference to the other cells. The average solids content of the control cell and cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] were very close.

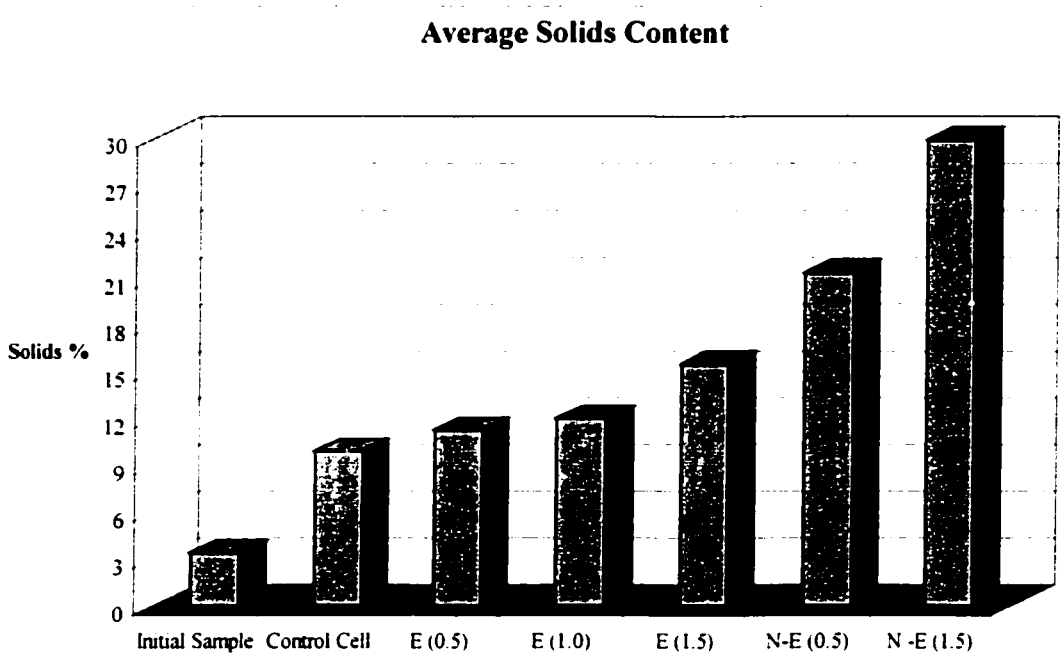


Figure 4 –2 Average solids content distribution in all cells

4-2) pH Value

Figure 4-3 illustrates the pH distribution in all cells at the end of the experiment. The pH value in the initial sample was 5.37. In the control cell the pH value was almost 6.9 without any remarkable changes between the electrodes. Generally the pH in the cathode area was higher than the anode area as expected. This could be a result of OH^- and H^+ formation in the cathode and the anode respectively due to the electrokinetic

processes. The highest pH gradient (3.56) between the cathode and the anode area was observed in cell #2 [N-E (1.5)]. The maximum and minimum pH values were 8.3 in the cathode area of cell #1 [N-E (0.5)] and 4.5 in the anode area of cell #5 [E (1)].

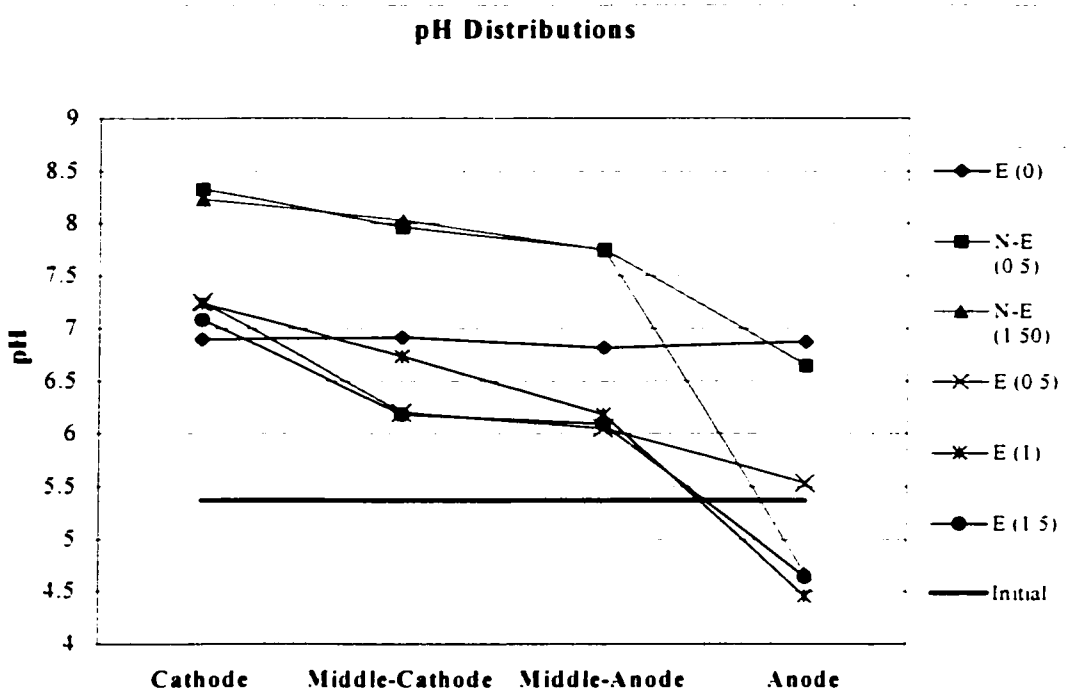


Figure 4 –3 pH distributions

In the anode area, the pH value of cell #2 [N-E (1.5)] was 6.64 but the pH value of cell #1 [N-E (0.5)] was 4.67 below the initial sample value.

The existence of the acid front is associated with cells having a high potential gradient. The addition of fertilizer increases a pH difference between middle and anode area. The pH value in the middle area is almost in the neutral region. The pH in cells #4 [E (0.5)], #5 [E (1)] and #6 [E (1.5)] was close to neutral in the cathode area. The application of 0.5 V/cm results in a smoother distribution of pH between electrodes (cell #1 and #4).

Generally cells #1 [N-E (0.5)] and #2 [N-E (1.5)] had higher pH values mostly in the cathode and middle areas compared to the other cells. Therefore, the effect of fertilizer in these changes is quite obvious and can have an impact on metal removal.

4-3) Organic Contents

Figure 4-4 shows the organic content in all cells. The initial sample had a higher organic content compared to all cells. In the cathode area organic content in all cells was almost equal. It dropped dramatically from the middle area to the anode in cells #1 [N-E (0.5)] and #2 [N-E (1.5)]. Organic content in the back anode area was 25% lower than the back cathode area in cell #1 [N-E (0.5)]. This amount was 16% in cell #2 [N-E (1.5)].

The decrease from the anode to cathode was by the amount of 6%, 12%, and 11% in cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] respectively. It was speculated that this drop was due to drainage in the cathode area.

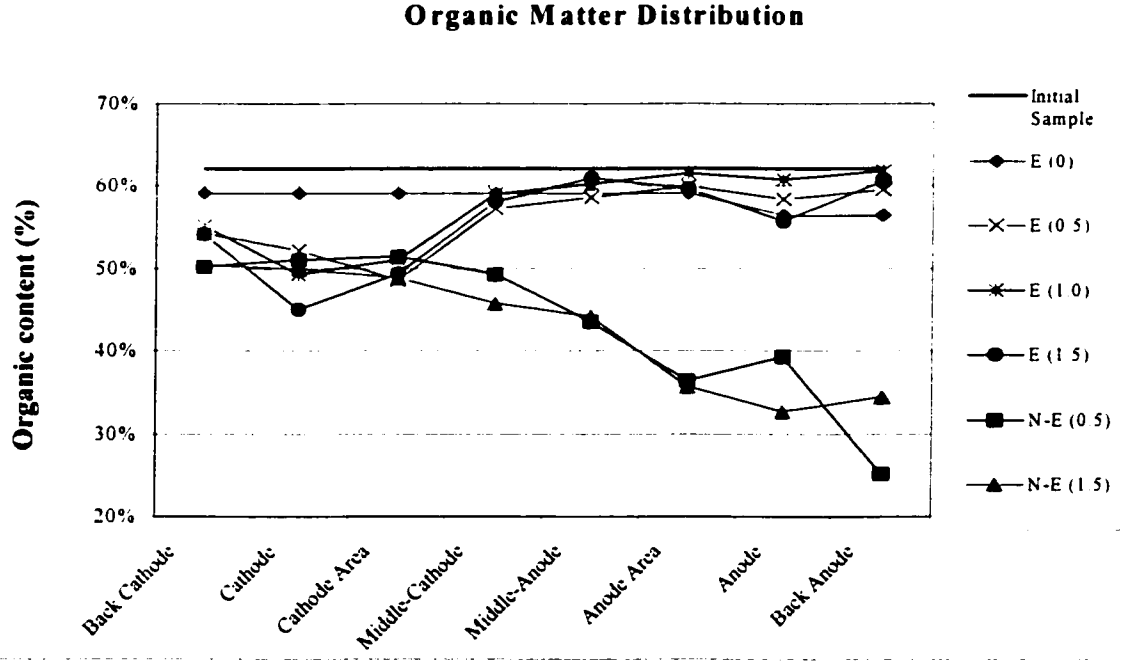


Figure 4 –4 Organic matter distributions

The lowest value of organic content was observed in the anode area of cell #1 [N-E (0.5)] and was equal to 25%. The average removal in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] is associated with electroosmotic flow into the cathode area. The fertilizer in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] promoted this removal with very high efficiency.

4-4) Chloride Contents

Figure 4-5 illustrates the chloride content in cell #1 [N-E (0.5)] and cell #2 [N-E (1.5)]. The figure also shows the total chloride in the initial sample from WWTP [initial (1)] and the chloride content after introducing the fertilizer to the system [initial (2)]. In both cells, a high reduction of chloride was observed compared to the initial sample.

The maximum chloride content in cell #1 [N-E (0.5)] was 8443 mg/ kg of dry solid in the middle anode. Variation of chloride content between the cathode and the anode was 2125 mg/ kg of dry solid.

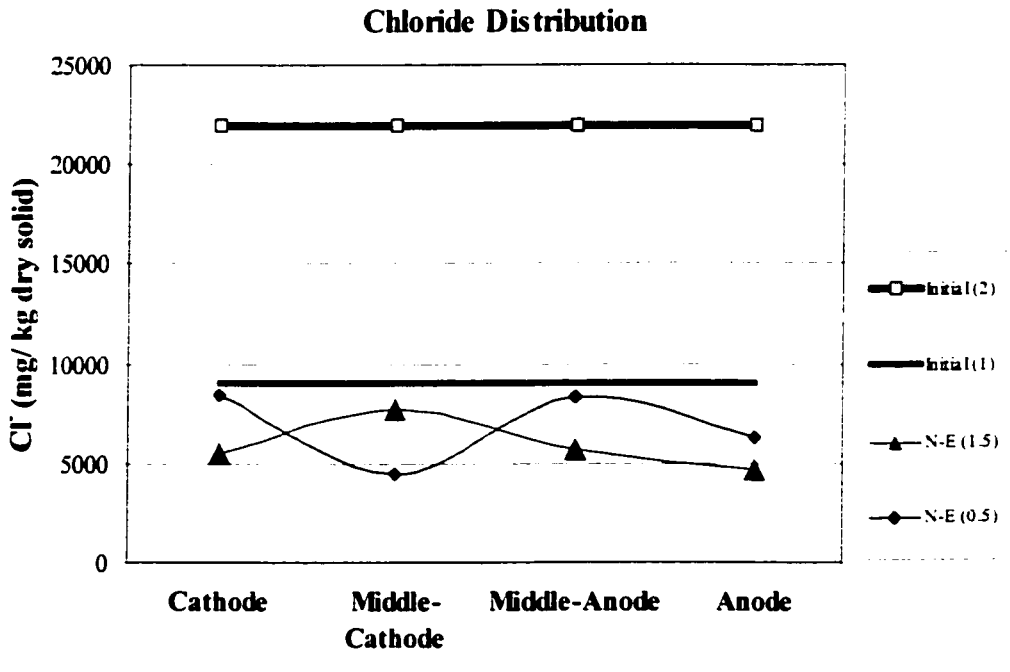


Figure 4-5 Chloride content distribution

In cell #2 [N-E (1.5)] the highest chloride content was 7760 mg/ kg of dry solid in the middle cathode area. The cathode area had higher amounts of chloride comparing to the anode. Variation of chloride content between the cathode and the anode was 851 mg/ kg of dry solid. The chloride distribution after 10 days of experiment implies that higher potential allows faster removal of chloride into the cathode, by creating higher electroosmotic flow.

Figure 4-6 shows the chloride content in cells #3 [E (0)], #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)]. Obviously, the chloride content in the control cell was lower than the initial sample and higher than the other cells. It could be concluded that chloride removal took place through the drainage system and that the electrokinetic process increased this removal.

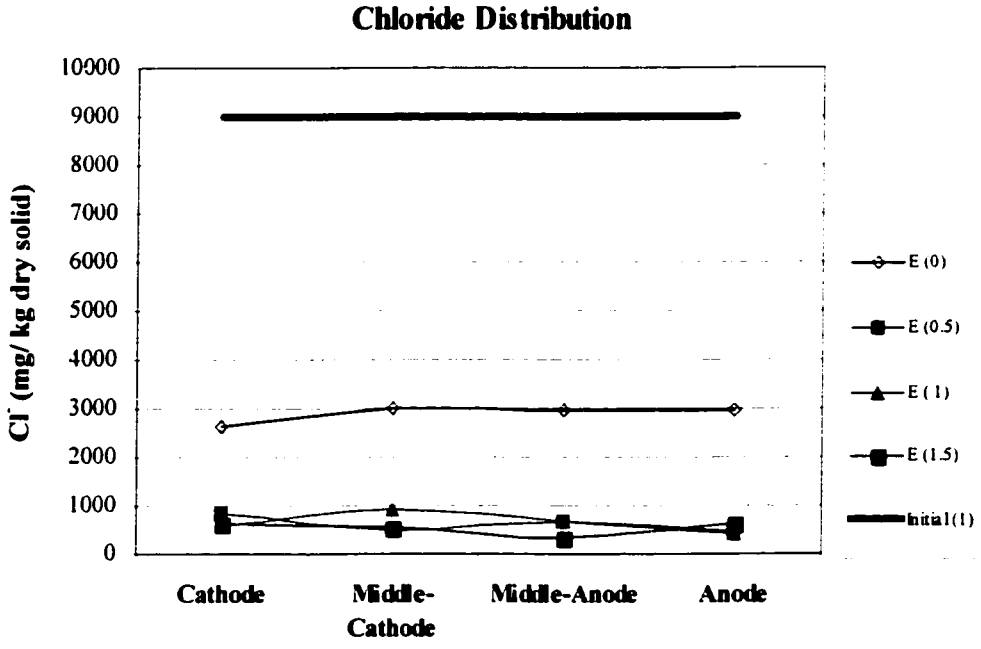


Figure 4-6 Chloride content distribution

Chloride content in the cathode area was higher than in the anode area in cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] and the variation between them was 403, 165, and 9 mg/ kg of dry solid respectively. These gradients showed that higher voltage produced more chloride removal.

The average chloride removal in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] was 69% and 73% respectively. This amount in cells #3 [E (0)], #4[E (0.5)], #5 [E (1)], and #6 [E (1.5)] was 68%, 92%, 93%, and 94% respectively. It shows that the drainage system and the higher voltage increases the chloride removal.

4-5) Sulfate Contents

Figure 4-7 contains the sulfate content in cells #1 [N-E (0.5)] and #2 [N-E (1.5)]. The initial sulfate content for these cells was a sum of the sulfate content in the sample from WWTP and the sulfate added to the system by the fertilizer [initial (2)]. At the end of the experiment both cells had less sulfate content than the initial sample.

In cell #1 [N-E (0.5)], the sulfate content decreased from the anode area to the cathode area. The variation of sulfate concentration between the anode and the cathode was 267 mg/ kg of dry solid. The average sulfate content in this cell was 178 mg/ kg of dry solid.

In cell #2 [N-E (1.5)] (the same as cell #1), the sulfate content decreased from the anode area to the cathode area. The variation of sulfate concentration between the anode and the cathode was 166 mg/ kg of dry solid. The average sulfate content in this cell is 91 mg/ kg of dry solid.

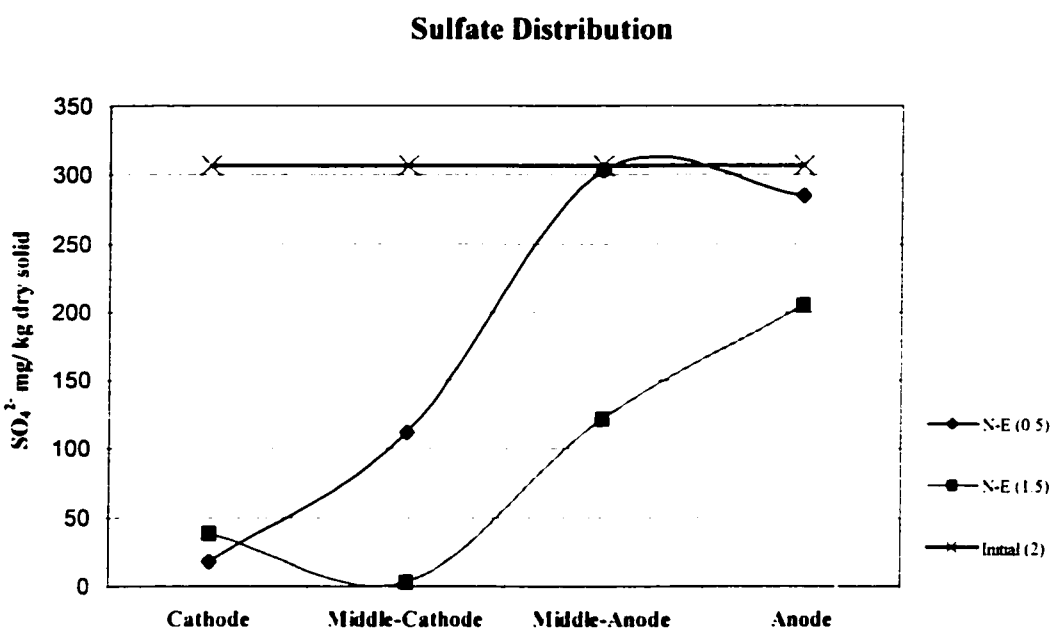


Figure 4-7 Sulfate content distribution

In cells #1 [N-E (0.5)] and #2 [N-E (1.5)], the decrease of sulfate concentration in the cathode area could be a result of the discharge of sulfate by the catholyte. This concentration was fairly high in the anode area.

Figure 4-8 shows the sulfate content in cells #3 [E (0)], #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)]. All of these cells had lower sulfate content than the initial (1) sample. In the control cell, the sulfate content was decreased from the anode area to the cathode area and generally it was lower than cells #4 [E (0.5)], #5 [E (1)], #6 [E (1.5)]. In cells #4, #5,and #6, the sulfate content in the anode area was higher than in the cathode area. Once more it was demonstrated the attraction of anode. This impact in cells without fertilizer was much lower.

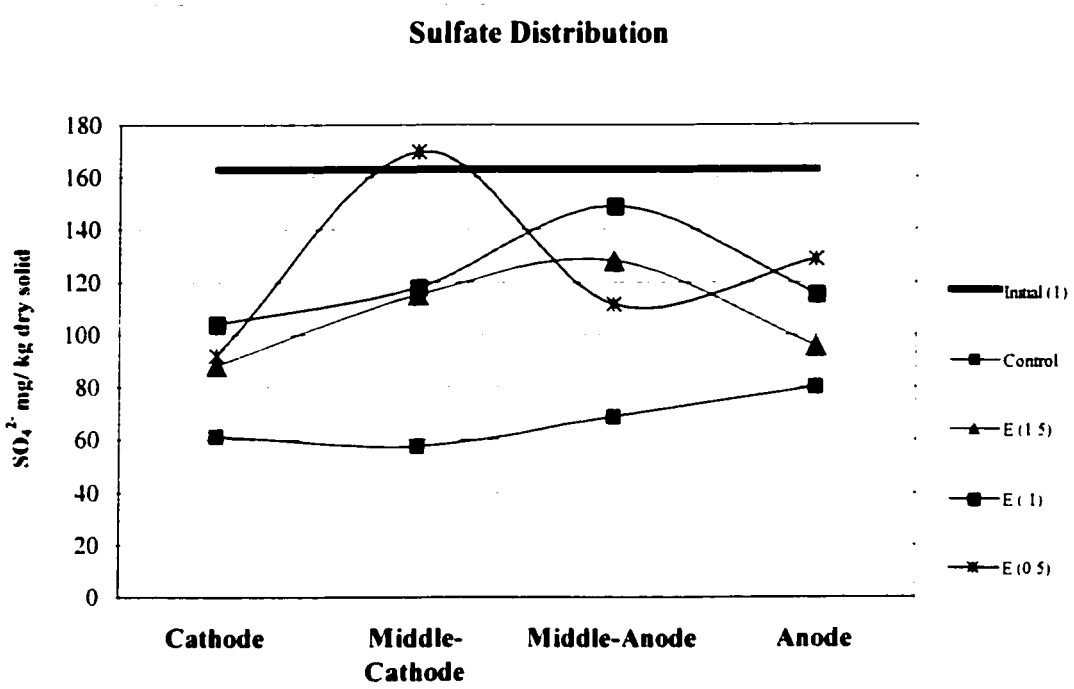


Figure 4-8 Sulfate content distribution

The average sulfate removal in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] was 42% and 71% respectively. This amount in cells #3 [E (0)], #4[E (0.5)], #5 [E (1)], and #6 [E (1.5)] was 59%, 23%, 25%, and 34% respectively. It shows that the drainage system, higher voltage, and fertilizer increase the sulfate removal.

4-6) Resistance Measurements

The variation of resistance variation with distance from the cathode for each cell is displayed in Figures 4-9 to 4-13. In all cells the resistance tended to increase from the cathode to the anode. In cell #1 [N-E (0.5)] the resistance variation between the cathode and the anode was not very high and varied very smoothly (Figure 4-9). The lowest and highest resistance variation between cathode and anode was around 24 Ohm and 47 Ohm on the 1st day and the 8th day of the experiment respectively.

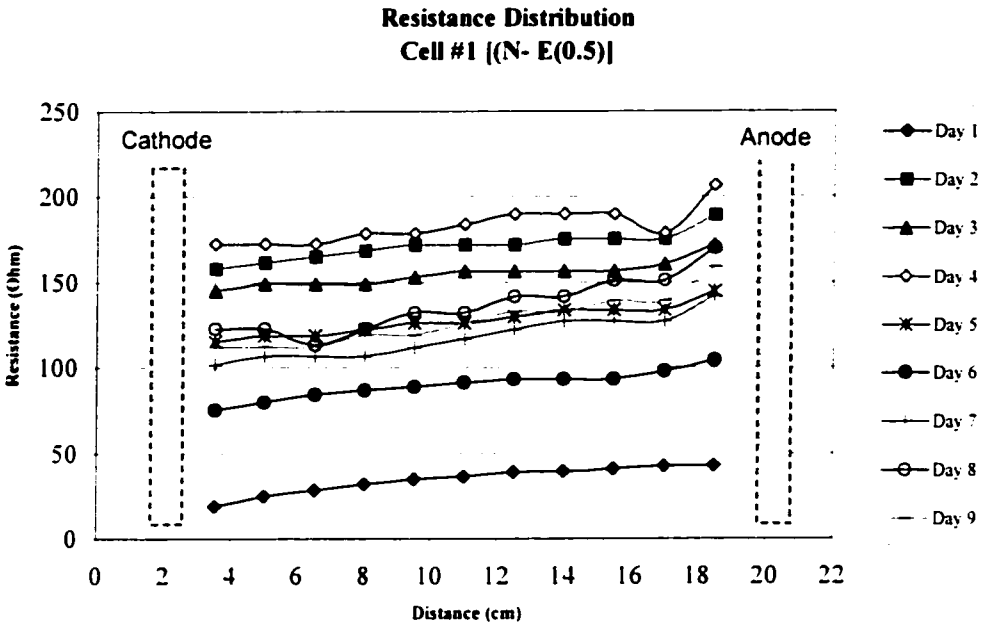


Figure 4-9 Resistance distribution in cell #1 [N-E (0.5)]

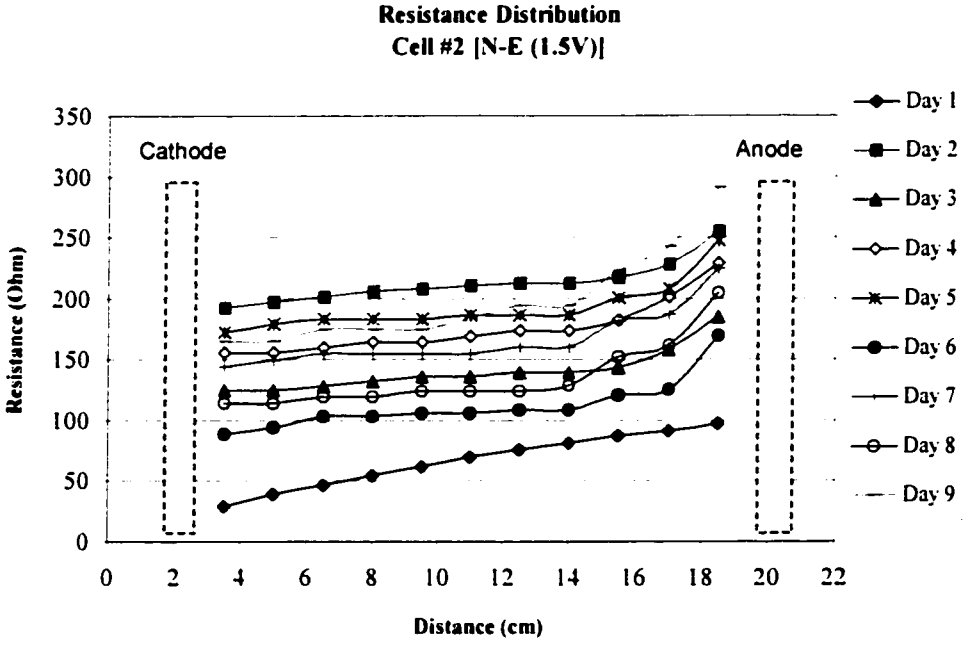


Figure 4-10 Resistance distribution in cell #2 [N-E (1.5)]

On the 5th day, the electrical current was disconnected and it was reconnected on the 6th day after 24 hours. The resistance dropped on the 6th day dramatically.

This resistance reduction could be as a result of the readjustment of water molecules and the reaching of the stability point after the disconnection of electrical current. In all distances the lowest and highest resistance were on the 1st and the 4th day respectively.

As time progressed, the resistance increased due to the dryness of the biosolids. Generally, the resistance in the anode was higher than in the cathode. This was as a result of more dryness in the anode area compared to the cathode area. In cell # 1 [N-E (0.5)] the highest resistance was 206.9 Ohm in the anode on the 4th day of the experiment.

Resistance curves for cell #2 [N-E (1.5)] are shown in Figure 4-10. The highest resistance was on the 2nd day and the lowest was on the 1st day. The resistance increased every day. After disconnection of the electrical current on the 5th day and reconnection on the 6th day, a high resistance reduction was observed.

The lowest and highest resistance variations between the cathode and the anode were 60.37 Ohm and 126.21 Ohm on the 3rd day and the 9th day of the experiment, respectively. The highest resistance was 291.26 Ohm in the anode on the 9th day of the experiment.

Figure 4-11 illustrates the resistance variation in cell #4 [E (0.5)]. It clearly shows that the resistance tended to increase from the cathode to the anode with a very high slope. The lowest amount of resistance was 109.76 Ohm on the first day and the highest amount was 2250 Ohm on the 10th day of experiment. Electrical current was disconnected on the 6th day and reconnected on the 7th day. A resistance drop was observed on the 7th day. After reconnection, the resistance started to increase gradually.

The lowest and highest resistance gradient between cathode and anode were 508.85 Ohm and 2000 Ohm on the 1st day and the 10th day of the experiment respectively.

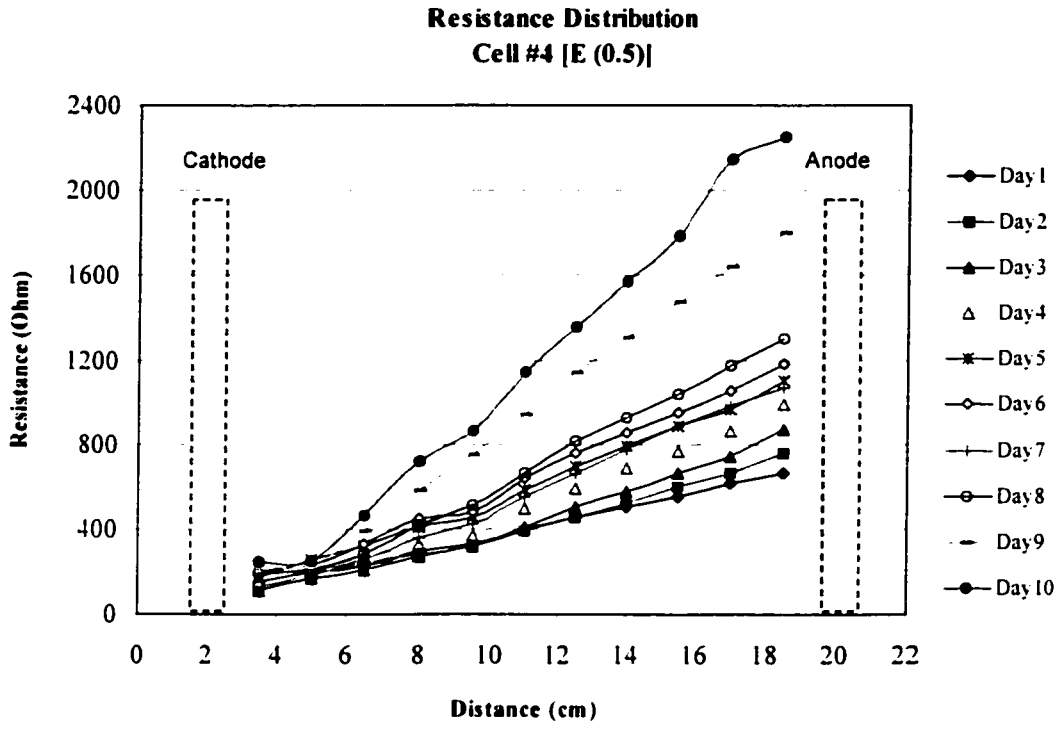


Figure 4-11 Resistance distribution in cell #4 [E (0.5)]

The resistance distributions of cell #5 [E (1.0)] are shown in Figure 4-12. The resistance increased daily from the cathode to the anode as expected. The lowest resistance was 109.09 Ohm on the 2nd day and the highest resistance was the 2950 on the 10th day.

The resistance dropped on the 7th day due to a 24-hour disconnection of electrical current. The lowest and highest resistance variations between the cathode and the anode were 490.11 Ohm and 2600 Ohm on the 1st and the 10th days of the experiment, respectively.

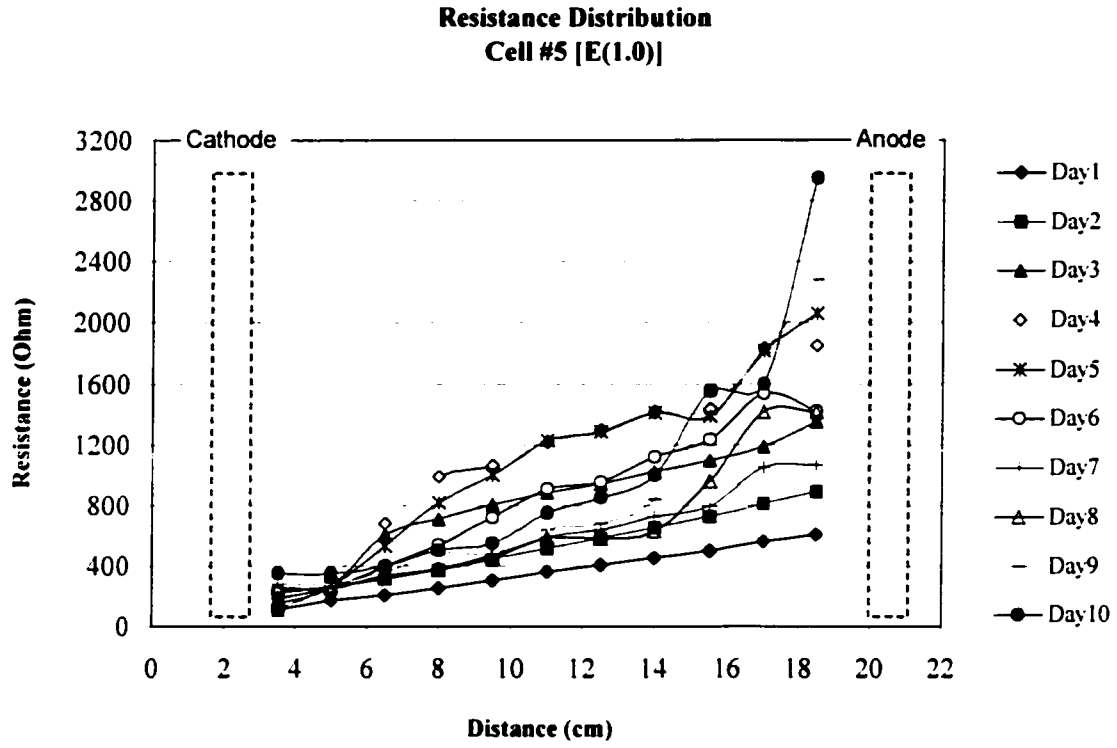


Figure 4-12 Resistance distribution in cell #5 [E (1)]

Figure 4-13 shows the resistance variation in cell #6 [E (1.5)]. The lowest value was 88 Ohm on the 1st day and the highest resistance was 16250 Ohm on the 10th day of the experiment. The resistance increased from the cathode to the anode very smoothly but on the days 8th, 9th, and 10th it jumped to higher resistance values. On all days the resistance variation from the cathode to the middle of the cell was very low but from the middle to the anode the variation was much higher.

Resistance reduction on the 7th day occurred because of the reconnection of electrical current after 24 hours disconnection. The lowest and highest resistance gradient between the cathode and the anode were 453.66 Ohm and 10863.64 Ohm on the 1st day and the 10th day of the experiment respectively.

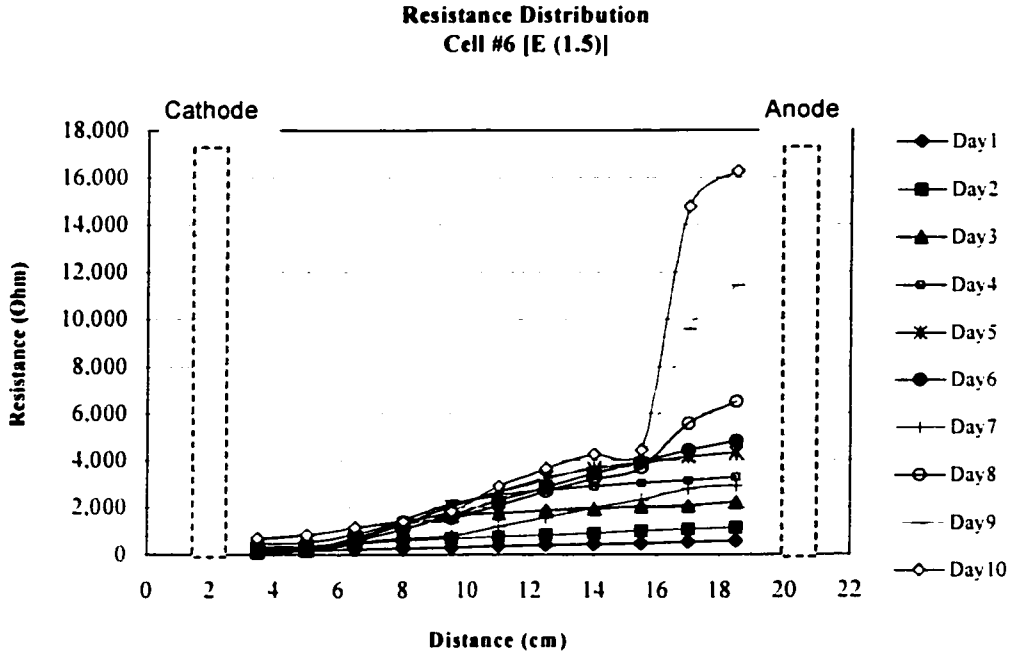


Figure 4-13 Resistance distribution in cell #6 [E (1.5)]

The maximum resistance in cell #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] was 2250, 2950, and 16250 Ohm, respectively. The minimum resistance in these cells was 109.76, 109.09, and 88 Ohm, respectively. The maximum resistances in cell #1 [N-E (0.5)] and #2 [N-E (1.5)] were 206.89 and 291 Ohm and the minimum amounts for these cells were 18.98 and 29 Ohm respectively. The ratio of highest resistance between cell #2 [N-E (1.5)] and cell #1 [N-E (0.5)] was 1.4 but this ratio between cell #6 [E (1.5)] and cell #4 [E (0.5)] was 7.2. These ratios show that higher voltage cause higher resistance but the presence of fertilizer decreases this value. The ratio of highest resistance between cell #4 [E (0.5)] and cell #1 [N-E (0.5)] is 10.9 and this ratio between cell #6 [E (1.5)] and cell #2 [N-E (1.5)] was 55.8. These ratios show the effect of fertilizer in the presence of a

fixed voltage. Fertilizer decreases the resistance remarkably. The comparison of resistance between all cells shows that fertilizer reduces the resistance gradient dramatically.

4-7) Power and Energy Consumption

Figure 4-14 illustrates the energy consumption in cell #1 [N-E (0.5)] and #2 [N-E (1.5)]. In cells #1 [N-E (0.5)] the highest and the lowest amounts were 1.233 W on the first day and 0.095 W on the 8^{th} day respectively. In cells #2 [N-E (1.5)] the highest amount was 5.400 W on the first day and the lowest amount was 0.278 W on the 9^{th} day.

The highest drop in the power consumption occurred on the first day in both cells. As the experiment progressed, the power consumption decreased smoothly. It could be as a result of dryness and the increase in the resistance. After reconnection of the system to the power supply (24 hours disconnection) on the 6^{th} day, an increase in the power consumption was observed which could be due to rearrangement of water molecules and the decrease in the resistance of the system.

Figure 4-15 shows the energy consumption in cell #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)]. The curve of cell #4 [E (0.5)] shows the lowest energy consumption. The slop of this curve is quite smooth and almost a straight line especially in the middle.

In cells #5 [E (1)] and #6 [E (1.5)], which had the same applied potential as in cells #1 [N-E (0.5)] and #2 [N-E (1.5)], the energy consumption had a huge drop on the first day and decreased every day thereafter. The increase of power consumption on the 7^{th} day is obviously due to the reconnection of the system to the power supply.

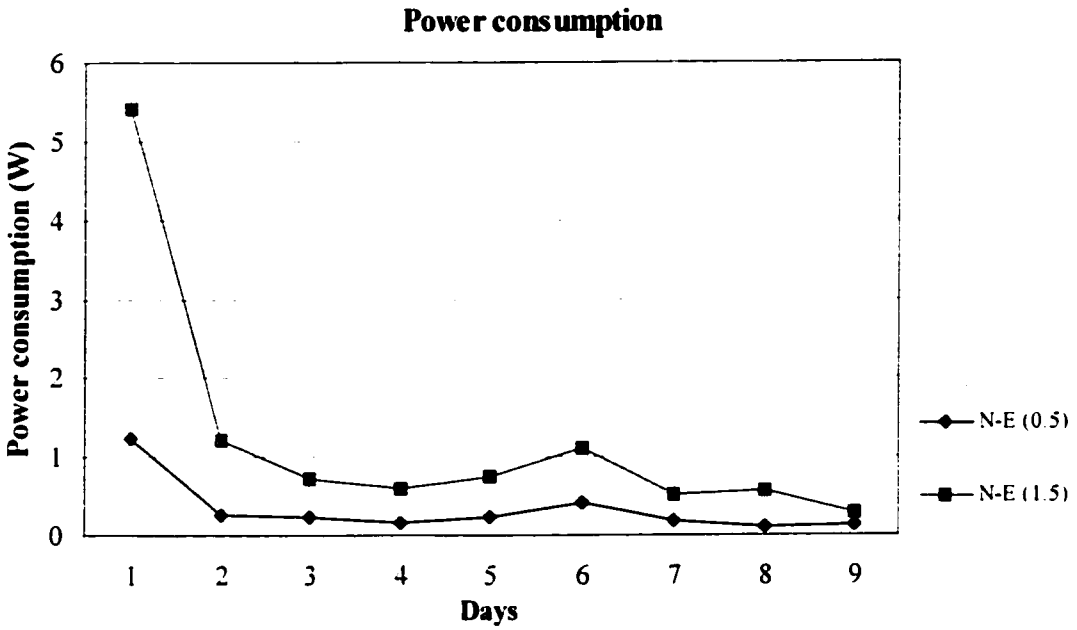


Figure 4-14 Power consumption distribution

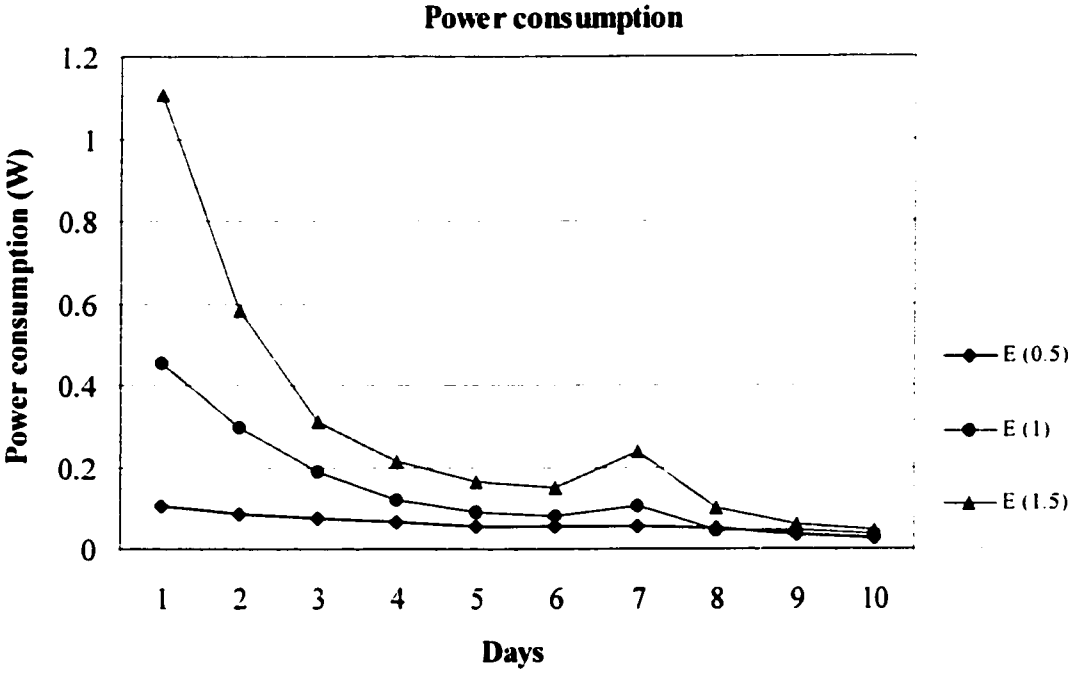


Figure 4-15 Power consumption distribution

By comparing the power consumption of cells #1 [N-E (0.5)] and #2 [N-E (1.5)] and also cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)], it can be deduced that the power consumption increased according to increases in voltage. Generally power consumption in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] was higher than cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)]. Therefore, it can be concluded that the effect of the fertilizer is to reduce the resistance and increase the efficiency of the electrokinetic processes.

Figure 4-16 summarizes the energy consumption of each cell during the experiment. The highest amount was 198.58 W.h in cell #2 [N-E (1.5)] with a huge difference compared to other cells.

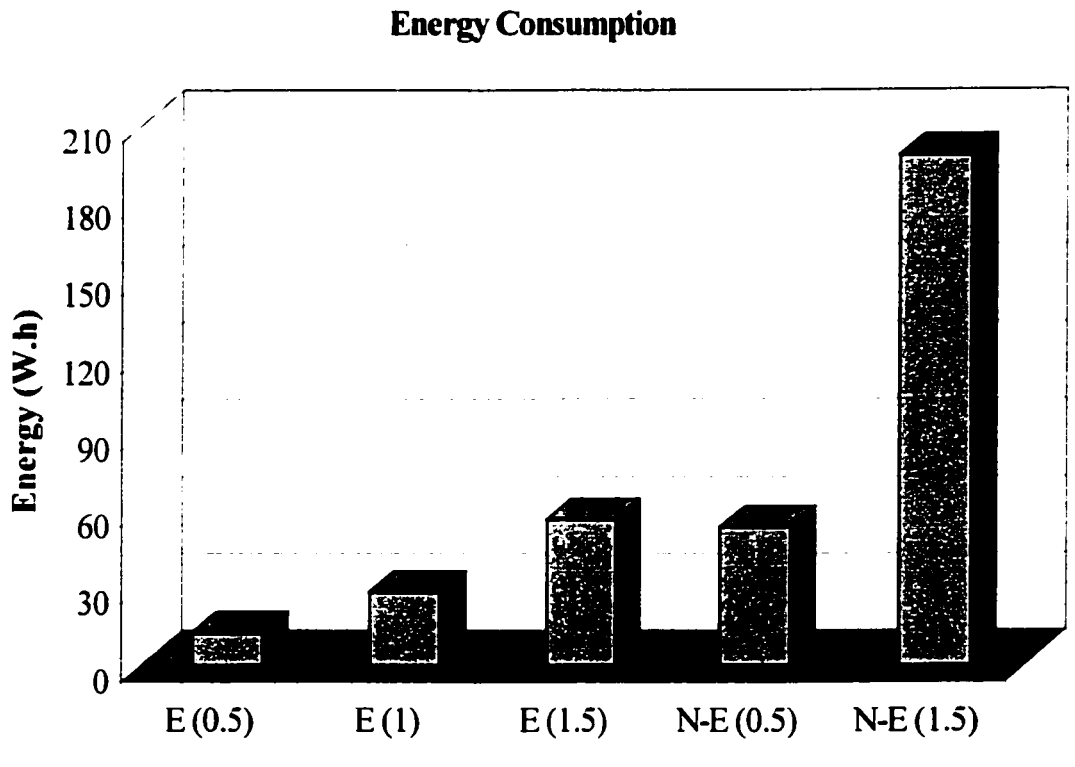


Figure 4-16 Energy consumption distribution

Table 4-1 shows the power consumption in all cells. By considering the amount of $0.03/kW.h. the cost of electric power is calculated for each cell. Cell #2 [N-E (1.5)] which showed the best results needs $ 6.62/ m^3 of biosolids in WWTP.

Table 4-1 Power consumption vs. volume of biosolids in cells

	E (0.5)	E (1)	E (1.5)	N-E (0.5)	N-E (1.5)
W.h	12.78	28.88	57.09	54.25	198.58
kW.h	0.0128	0.0289	0.0571	0.0542	0.1986
kW.h / m^3 of biosolids	14.196	32.088	63.432	60.276	220.644
$/$m^3$ of biosolids	0.42	0.96	1.90	1.80	6.62

4-8) Measurements of pH and Volume of Catholyte

The volume and the pH of the catholyte were measured every day. Table 4-2 summarizes the pH value of the catholyte in each cell on the first day of experiment. Figure 4-17 shows the volume of the catholyte in each day of the experiment.

Table 4-2 pH of catholyte in each cell

Cell	**#1 [N-E (0.5)]**	**#2 [N-E (1.5)]**	**#3 [E (0)]**	**#4 [E(0.5)]**	**#5 [E(1)]**	**#6 [E(1.5)]**
pH	11.8	12.0	7.5	10.1	11.9	12.0

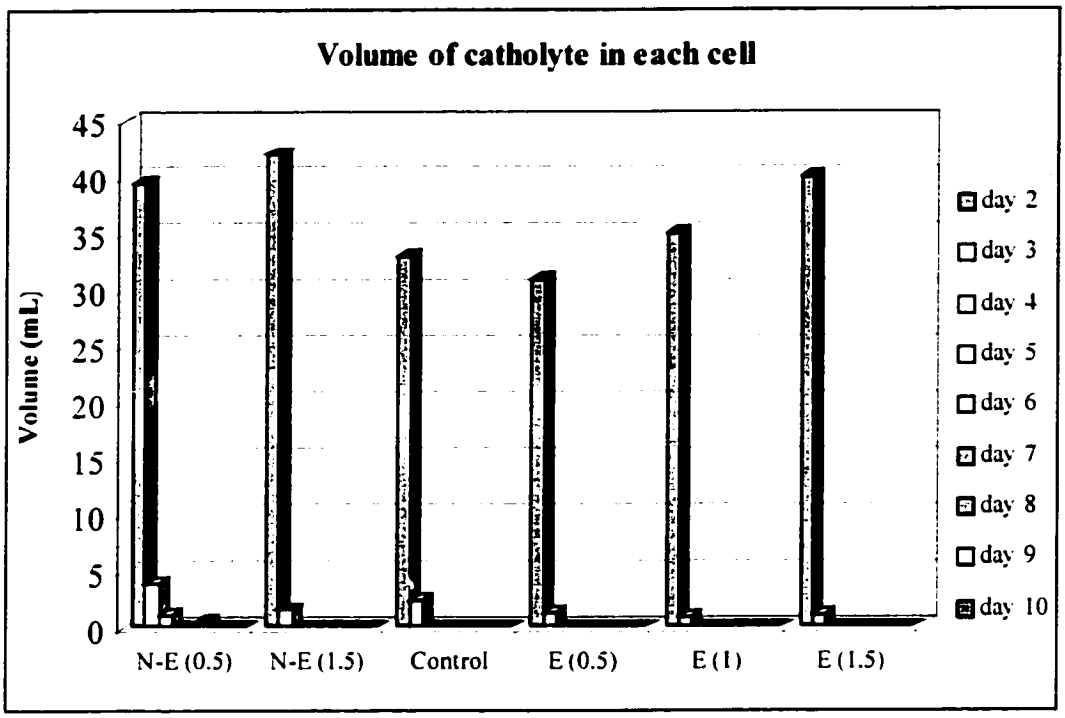


Figure 4-17 Volume of catholyte in each cell after connection to electricity

4-9) Coefficient of EO Permeability (K_E)

As mentioned in chapter one, the electroosmotic flow rate could be calculated using equation 2.1. All parameters in this equation are measured during this experiment except coefficient of EO permeability (K_E). All cells had two amounts of catholytes for 2nd and 3rd days of the experiment. Table 4-3 summarizes K_E value for all cells. The results show that K_E is almost the same in all cells and voltage difference and addition of fertilizer had no effect on this value.

Table 4-3 Coefficient of EO permeability (K_E) in all cells

Cells	Time	Catholyte (mL)	Q (mL/s)	E (V/cm)	A (cm^2)	K_E (cm^2/V.s)
E (0.5)	2nd day	31	3.59 E-04	0.5	23.5	3.05 E-05
	3rd day	1.2	1.39 E-05	0.5	23.5	1.18 E-06
E (1)	2nd day	55	6.37 E-04	1	23.5	2.71 E-05
	3rd day	0.8	9.26E-06	1	23.5	3.94 E-07
E (1.5)	2nd day	40	4.63 E-04	1.5	23.5	1.31 E-05
	3rd day	1.1	1.27 E-05	1.5	23.5	3.61 E-07
N-E (0.5)	2nd day	42	4.86 E-04	0.5	23.5	4.13 E-05
	3rd day	3.8	4.40 E-05	0.5	23.5	3.74 E-06
N-E (1.5)	2nd day	39.5	4.57 E-04	1.5	23.5	1.30 E-05
	3rd day	1.5	1.736 E-05	1.5	23.5	4.93 E-07

4-10) Metal Content

To determine the movement of metals in the cells, a metal content test was carried out for lead, cadmium, copper, zinc, nickel, and iron. This test was also performed on the initial sample to estimate the initial content for each metal as a reference for comparison. Description of the results for each metal is as follows.

4-10-1) Lead Content

Table 4-4 and Figure 4-18 illustrate the lead distribution in all cells. Lead concentration was lower in all cells compared to the initial value. This concentration decreased more in the cathode area than in the anode area. It can be deduced that movement of Pb from the anode area to the cathode area was due to the drainage system supported by electroosmotic flow.

Table 4-4 Lead distribution in cells (mg/ kg of dry solid)

Cells / Samples	Initial	E (0)	E (1)	E (1.5)	E (0.5)	N-E (0.5)	N-E (1.5)
Cathode	37	24	18	14	12	21	< DL
Mid-cathode	37	24	25	14	< DL*	6	< DL
Mid-anode	37	27	29	32	25	< DL	< DL
Anode	37	27	26	25	16	< DL	< DL

* DL = Detection Limit

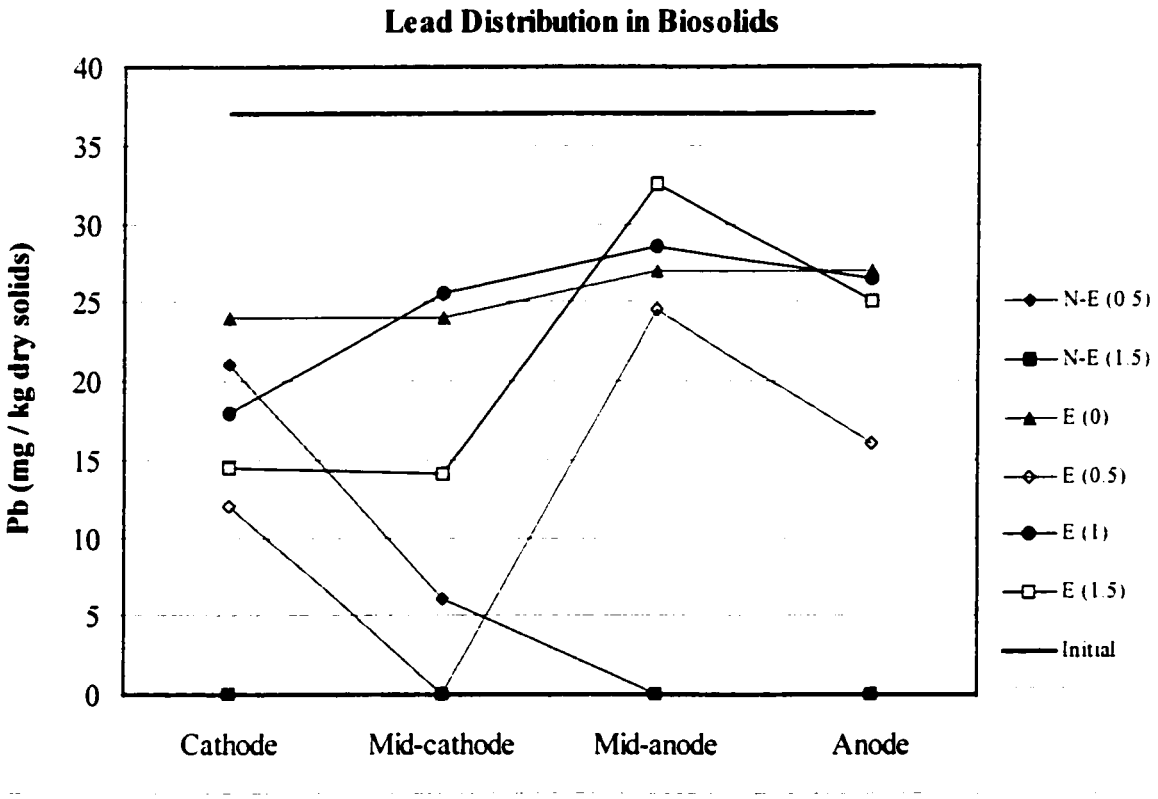


Figure 4- 18 Lead distribution in cells

Obviously, the lead content in the control cell was higher than in the cells with electrical current, which confirms the effect of electroosmotic process in this removal.

The reason for the high concentration of lead in the cathode area could be the formation of some complexes such as $Pb(OH)^+$ and $PbCl^+$, and their movement to the cathode.

The average lead removal in cells #1 and #2 was 82% and 100% respectively. This amount in cells #3, #4, #5, and #6 was 31%, 64%, 34%, and 42% respectively. Cells #1 [N-E (0.5)] and #2 [N-E (1.5)] show very good removal of lead. Cell #2 [N-E (1.5)] showed complete removal of Pb. In cell #1 [N-E (0.5)]. Pb concentration was non-detectable in the anode area and the middle anode area.

4-10-2) Cadmium Content

Concentration of cadmium in the initial sample was 0.2 mg/ kg of dry solid. Cadmium was not detected in samples after the experiment. Complete removal in all cells could be due to the movement of Cd with water through the drainage system.

4-10-3) Copper Content

Table 4-5 and Figure 4-19 show the copper distribution in all cells. Cu concentration in the anode area was higher than the cathode area. Slop of this reduction was very sharp from the anode to the middle anode and it was smoother from the middle cathode to the cathode area.

Table 4-5 Copper distribution in cells (mg/ kg of dry solid)

Cells / Samples	E (0.5)	E (1)	E (1.5)	N-E (1.5)	N-E (0.5)	E (0)	Initial
Cathode	305	385	230	260	275	305	310
Mid-cathode	310	280	260	45	75	305	310
Mid-anode	305	2 495	325	30	20	335	310
Anode	9 141	17 491	10 640	3 921	2 365	335	310

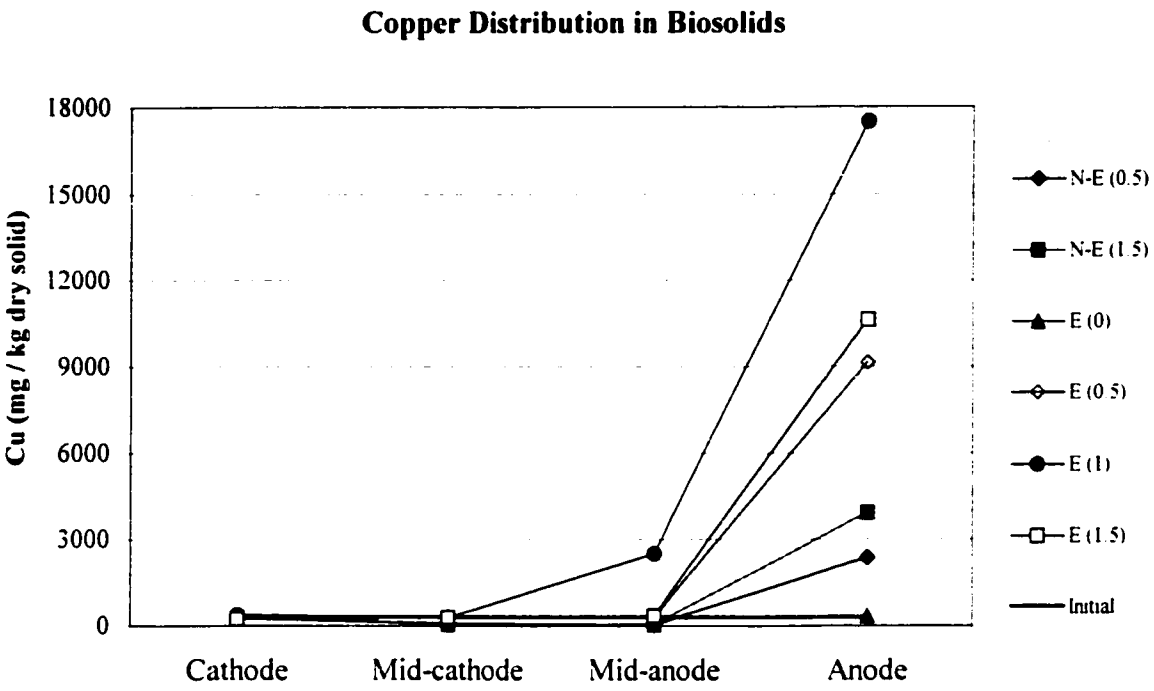


Figure 4-19 Copper distribution in cells

According to Merian (1991), Table 4-6 summarizes the influence of pH on the relative mobility of metal cations.

Table 4-6 Influence of pH on mobility of metals cations [Merian (1991)]

pH Range	Very Mobile	Moderately Mobile	Slowly Mobile
4.2 – 6.6	Cd, Hg, Ni, Zn	As, Be, Cr	Cu, Pb, Se
6.7 – 8.8	As, Cr	Be, Cd, Hg, Zn	Cu, Pb, Ni

The copper concentration in the control cell and the initial sample was almost the same. Therefore, the reason for the increase in Cu concentration in the cells with electrical current could be the corrosion of the anode and consequently the entry of copper into the system. Table 4-6 could explain the accumulation of copper in the anode area. According to this table, copper has low mobility in all ranges of pH. It could be

concluded that the released Cu due to the corrosion of the anode moved only to the anode and middle anode area.

Cells #5 [E (1)], #6 [E (1.5)], and #4 [E (0.5)] had the highest amount of copper respectively, especially in the anode area. Cathode areas of cell #6 [E (1.5)] showed lower Cu content than the initial sample. The lowest amount of Cu was 20 (mg/ kg dry solid) in cell #1 [N-E (0.5)]. In cells #1 [N-E (0.5)] and #2 [N-E (1.5)], the Cu concentration in the anode area was less than in other cells. Also, the Cu concentration was lower than the initial sample in the middle and cathode area. It could be deduced that the electrokinetic process had reduced the Cu concentration in the cathode and middle areas. Obviously, the addition of fertilizer increased the efficiency of this removal in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] and reduced corrosion of the anode.

4-10-4) Zinc Content

Table 4-7 and Figure 4-20 show the zinc distribution in all cells after the experiment. The lowest amount was observed 50 mg/ kg of dry solid in cell #2 [N-E (1.5)].

Cells #3 [E (0)], #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] showed an increase in Zn concentration in the anode and middle anode area and a decrease in the cathode and middle cathode areas compared to the initial sample. The increase of zinc concentration in the anode area could be as a result of the attraction of Zn complexes such as $[Zn(OH)_4]^{2-}$ to that area.

The concentration of zinc in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] was much lower than the initial sample. This means that the removal of Zn was very successful thanks to the addition of fertilizer to these cells. In these two cells, the concentration of

zinc in the cathode area was higher than in the anode area. This could be due to movement of zinc to the cathode area.

Average zinc content in the cell with fertilizer and 1.5 V/cm is 84% lower than the initial sample. So the removal of zinc is promoted by using fertilizer and a higher voltage. Cells with fertilizer have 85% lower zinc content than cells without fertilizer. Cells with higher voltages also have nearly 25% lower zinc content than those with lower voltages.

Table 4-7 Zinc distribution in all cells (mg/ kg dry solid)

Cells / Samples	E (0.5)	E (1)	E (1.5)	E (0)	N-E (0.5)	N-E (1.5)	Initial
Cathode	510	515	425	660	325	175	685
Middle-cathode	670	585	540	660	135	70	685
Middle-anode	816	1 540	1 060	795	55	50	685
Anode	1 720	810	975	795	105	145	685

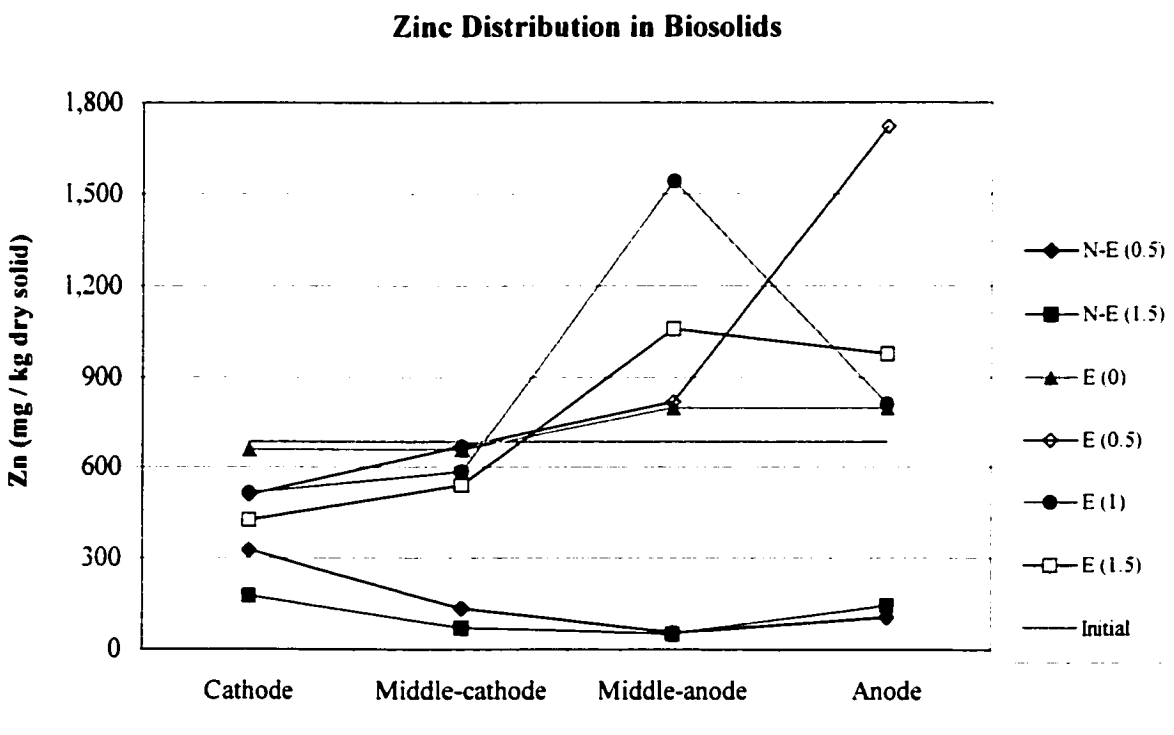


Figure 4-20 Zinc distribution in cells

4-10-5) Nickel Content

Table 4-8 and Figure 4-21 illustrate the nickel distribution in all cells. The amount of nickel in cells #1 [N-E (0.5)] and #2 [N-E (1.5)] was found to be below the detection limit (DL).

All cells except the control cell had higher amounts of Ni compared to the initial sample. Curves show a movement of nickel from the anode area to the cathode area. The concentration of Ni in the control cell was lower than the initial sample. The movement of nickel with water due to the drainage system could be the reason for the Ni reduction in the control cell. It could be concluded that the corrosion of the anode increased the concentration of Ni in the system. The highest amount of corrosion was observed in cell #6 [E (1.5)] which had the highest value of nickel in the biosolids. According to Merian (1991), in the pH range between 4.2 to 6.6, nickel is very mobile and in the pH range between 6.7 to 8.8, it is slightly mobile.

With reference to the pH results, the anode area had low pH. Therefore, Ni that was released from the anode due to corrosion had moved easily to the middle area. In the middle area, due to the higher pH, the rate of nickel movement decreased and caused Ni accumulation.

Table 4-8 Nickel distribution in cells (mg/ kg of dry solid)

Cells / Samples	E (1.5)	E (1)	E (0.5)	N-E (0.5)	N-E (1.5)	E (0)	Initial
Cathode	17 497	530	750	< DL*	< DL	15	105
Mid-cathode	55 505	27 486	2 859	< DL	< DL	15	105
Mid-anode	86 461	29 502	24 521	< DL	90	40	105
Anode	2 000	150	12 001	16 497	2 400	40	105

* DL = Detection Limit

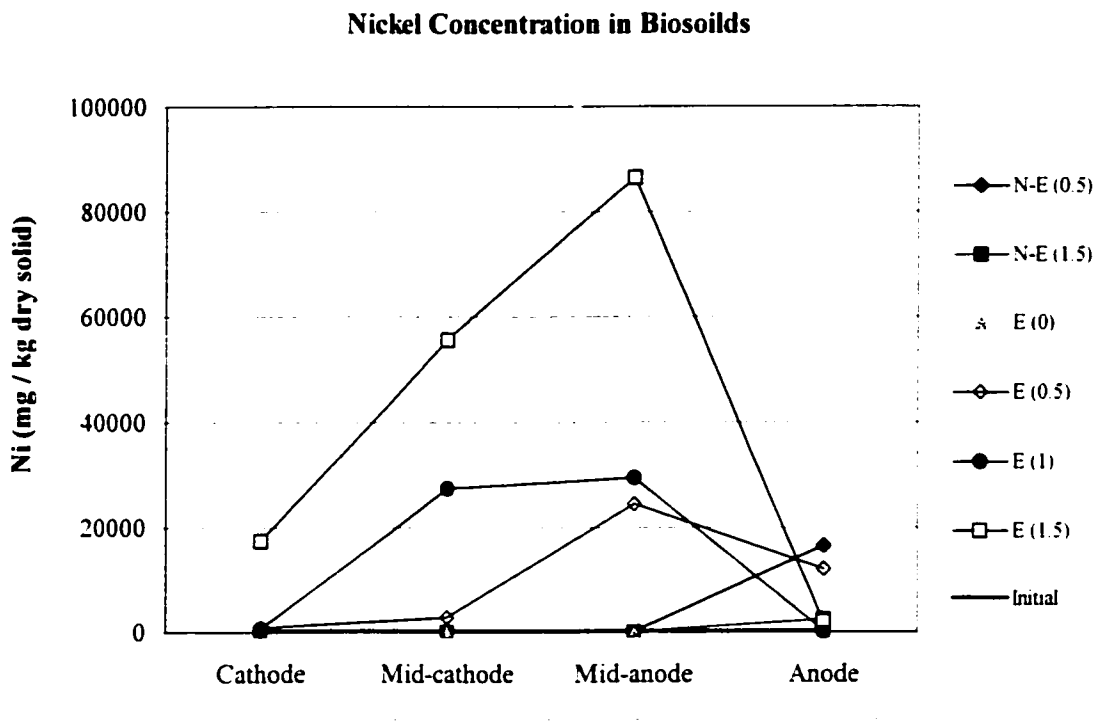


Figure 4-21 Nickel distribution in cells

In cells #1 [N-E (0.5)] and #2 [N-E (1.5)] nickel concentration was below detection limit except in the anode area. These two cells had the best nickel removal (Table 4-8). Having less corrosion in the anode had reduced the Ni concentration in this area. The elecrokinetic process increased the removal of nickel from the system. As shown in Table 4-8, cell #2 [N-E (1.5)] had higher removal than cell #1 [N-E (0.5)].

4-10-6) Iron Content

Table 4-9 and Figure 4-22 show the iron concentration in all cells. The control cell had almost the same value as the initial sample. Cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)] had a very large increase in iron concentration, especially in their cathode area. It could be due to the corrosion of anode and the movement of iron under the influence of

electrical potential. The slope of curves in these cells was very sharp between the middle and the cathode area. An accumulation of Fe was observed in the cathode area.

Cell #1 [N-E (0.5)] and #2 [N-E (1.5)] had lower iron concentration in comparison to an initial sample. Anodes in these two cells had little corrosion during the experiment, which means that the entry of iron into the system was quite low compared to cells #4 [E (0.5)], #5 [E (1)], and #6 [E (1.5)]. The electrokinetic process thanks to the addition of fertilizer to these cells could be the reason for the improved removal of iron.

Table 4-9 Iron distribution in cells (mg/ kg of dry solid)

Cells / Samples	E (1.5)	E (1)	E (0.5)	E (0)	Initial	N-E (0.5)	N-E (1.5)
Cathode	112 480	84 996	69 484	18 992	21 920	15 495	2 615
Mid-cathode	80 008	67 467	60 475	18 992	21 920	2 185	1 660
Mid-anode	58 474	41 503	62 054	25 002	21 920	1 135	1 345
Anode	73 500	39 980	76 505	25 002	21 920	6 499	2 525

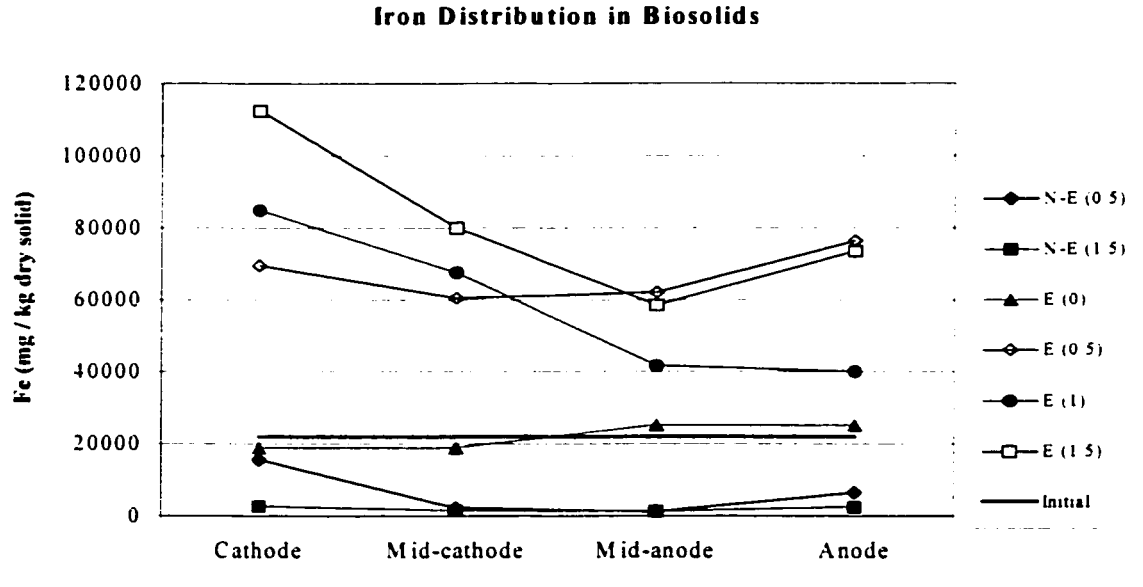


Figure 4-22 Iron distribution in cells

4-11) Fecal Coliform

The fecal coliform test as an indicator of pathogen existence was carried out on initial samples (two samples), distilled water (as reference), and samples taken from cells #1 [N-E (0.5)], #2 [N-E (1.5)], #4 [E (0.5)], and #6 [E (1.5)]. Three samples from these cells were taken from the cathode, middle and anode areas. Table 4-10 summarizes all results.

The result of distilled water was negative and it showed that there is no mistake or contamination during the test. The results of initial samples were positive and both plates had almost the same number of colonies.

In cells #1 [N-E (0.5)] and #2 [N-E (1.5)] the results were negative for all points, which implies the elimination of pathogens. In cell #4 [E (0.5)] the results were positive in the cathode and negative in the middle and anode areas.

Table 4-10 Fecal coliform test results

Samples / Cells	Cathode	Middle	Anode
Cell #1 [N-E (0.5)]	Negative	Negative	Negative
Cell #2 [N-E (1.5)]	Negative	Negative	Negative
Cell #4 [E (0.5)]	Positive	Negative	Negative
Cell #6 [E (1.5)]	Positive	Positive	Negative
Initial sample (1)	Positive		
Initial sample (2)	Positive		
Distilled water	Negative		

In cell #6 [E (1.5)] the results were positive in the cathode and middle areas, and it was negative in the anode area. The positive results in these cells were not the same as the initial sample. The reduction in the number of colonies was observed but its complete destruction was not achieved.

Chapter 5

Conclusions

This investigation permitted the development of a new technology, which is able to improve the quality of biosolids by applying the electrokinetic phenomena to achieve simultaneous removal of water, heavy metals, pathogen, and organic matter.

The results from this experiment allow making the following conclusions.

- The highest amount of solids content, which is 62%, was observed in the anode area in the cell with fertilizer and a potential gradient of 1.5 V/cm. This amount was 95% higher than the solids content in the initial sample.
- The cell with fertilizer and 1.5 V/cm had 89% higher average solids content compared to the initial sample.
- The average solids content in cells with fertilizer was 48% higher than cells without fertilizer.
- Average solids content in cells with higher voltage (1.5 V/cm) was 28 % higher than cells with lower voltage (0.5 V/cm).
- It was found that this investigation had a very short operation time. The first 72 hours were the most effective operating time in this experiment.
- The lowest amount of organic content in the cell with fertilizer (1.5 V/cm) was found to be 33% in the anode area. This content was 47% lower than the initial sample.
- The organic content in cells with fertilizer was almost 40% lower in the anode area.
- Average value of organic content in the cell with fertilizer (1.5 V/cm) was 43 %.

- The average zinc content in cells with fertilizer (1.5 V/cm) was 84% lower than in the initial sample.
- Removal of zinc depends on the fertilizer content and voltage. Cells with fertilizer had 85% lower zinc content than cells without fertilizer. Cells at higher voltages had almost 25% lower zinc content than those at lower voltages.
- The concentration of cadmium in initial samples was low (0.2 mg/ kg of dry solid) and the cadmium was not detected after the experiment in all cells.
- Cells with fertilizer exhibited the highest level of lead removal. The lead content in all areas of the cell with fertilizer (1.5 V/cm) was non-detectable after the experiment.
- High levels of iron removal were observed in cells with fertilizer. The concentration of iron in the cell with fertilizer and 1.5 V/cm was 91% lower than in the initial sample.
- Cells with fertilizer showed a higher removal of Ni than the other cells. The best result was observed in cells with higher voltages.
- Cells with fertilizer show a higher removal of Cu than the other cells. The best result was observed in cells with higher voltages.
- In all cells corrosion of the anode introduced supplementary metals to the system. The application of new materials for anode is necessary.
- The electrokinetic phenomena affected the elimination of pathogens.
- No fecal coliform indicators were observed in cells with fertilizer.
- The rate of increase of the resistance with distance from cathode to anode in cells with fertilizer was much lower (300 Ohm) than the cells without fertilizer (16,000 Ohm).

- The electrokinetic phenomena increased the pH value of biosolids. The pH value of control cell was 7.48, however, the pH value in the other cells was around 11. The pH value was independent of fertilizer content as well as voltage variation.
- The corrosion of the anode in cells with fertilizer was much lower than other cells. This phenomenon may reduce the equipment maintenance costs.
- The clearness of the catholyte depends on fertilizer content and voltage. The catholyte from cells with fertilizer was clearer than other cells. In addition, the application of a higher voltage increased the clearness.
- At the optimal removal conditions, which are expressed in cell #2 [N-E (1.5)], the consumption of energy was 220 kW.h / m^3 of biosolids.
- According to the rate of $0.03/kW.h, cost of electric power associated with the electrokinetic phenomena in the optimal conditions (cell #2 [N-E (1.5)]) is $ 6.62/ m^3 of biosolids.
- Results showed that the new developed cost-effective technology is capable to replace several units in WWTP including dewatering, disinfection, metal removal, and organic matter reduction. Therefore, this method is able to reduce capital, labor and operation costs significantly.

The developed electrokinetic treatment method for biosolids revitalization is simple, cost-effective and reliable. This method is able to not only produce biosolids with a high solids content (> 60%) but also reduces the amount of metals and organic matter with high efficiency. This technology can also eliminate the risk of infection of human, animals, and plants due to removal of pathogen. All the aforementioned results make this technology unique and useful for all municipal and industrial WWTP.

Recommendations

- To investigate the impact of different voltage values
- To use other conditioner liquids
- To apply different dosages of DAP
- To investigate the effect of electrodes in different shape and size
- To use other types of material as electrodes
- To investigate the effect of cell configuration using other shapes of electrokinetic cell is recommended.
- To investigate the mass balance in the system, analysis of catholyte is necessary
- To develop mathematical models.

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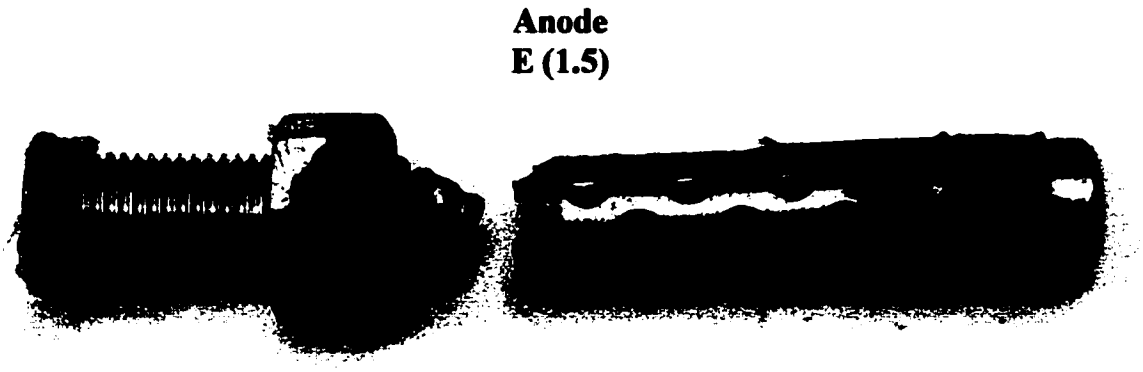
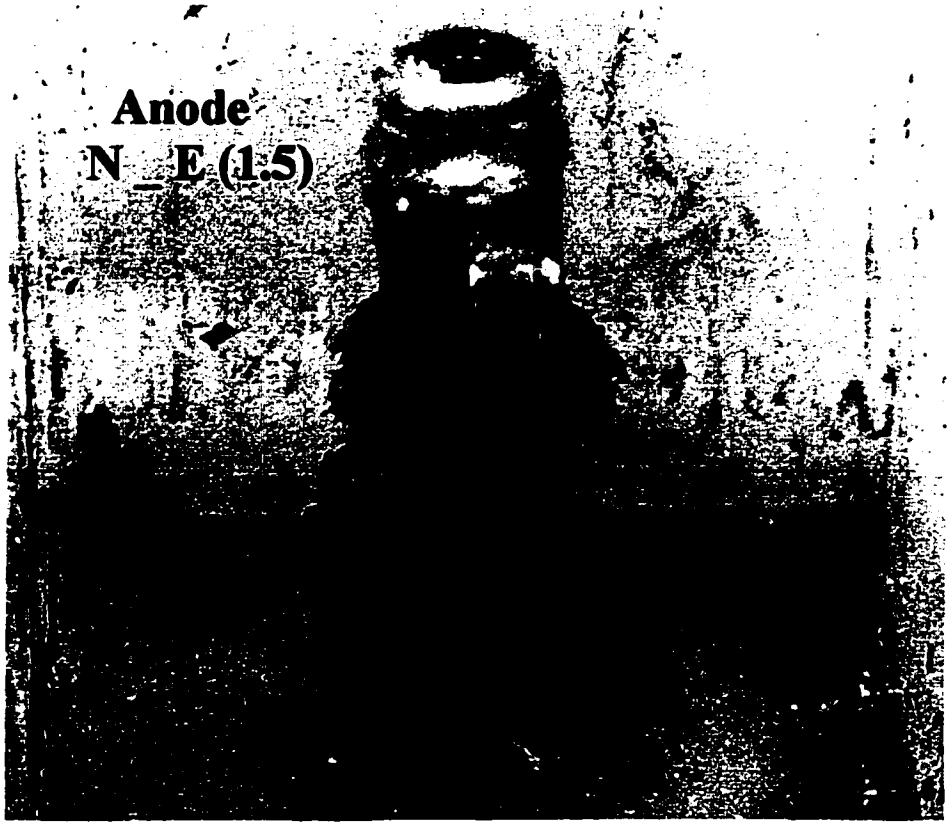
Appendix

-Photographs

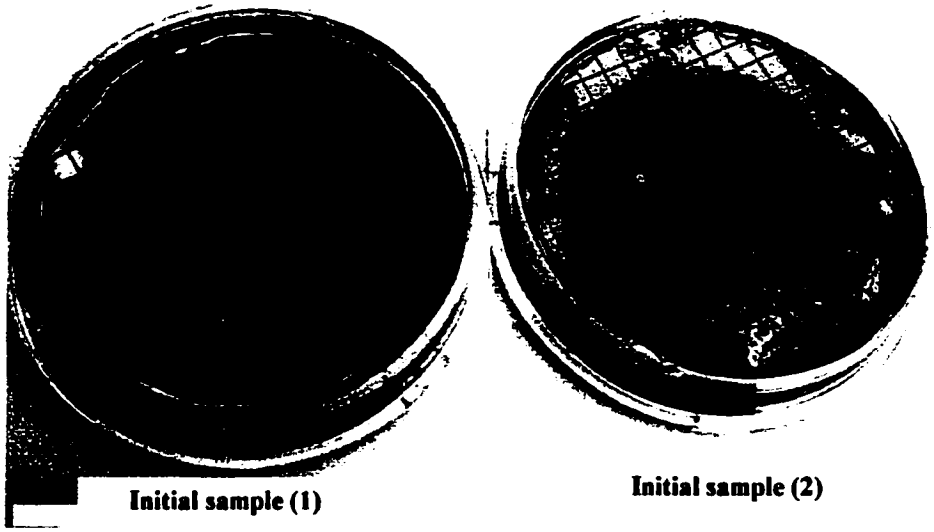


(a) Anode in cell #6 [E (1.5)]

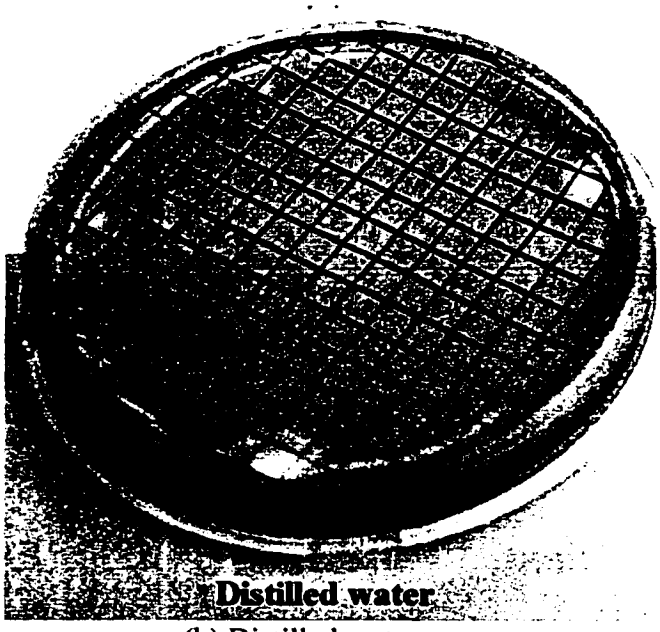


(b) Anode in cell #2 [N-E (1.5)]

Figure A-1 Corrosion comparison between cells with and without fertilizer



(a) Two samples from Initial sludge



(b) Distilled water

Figure A-2 Fecal coliform test results (distilled water and initial samples)

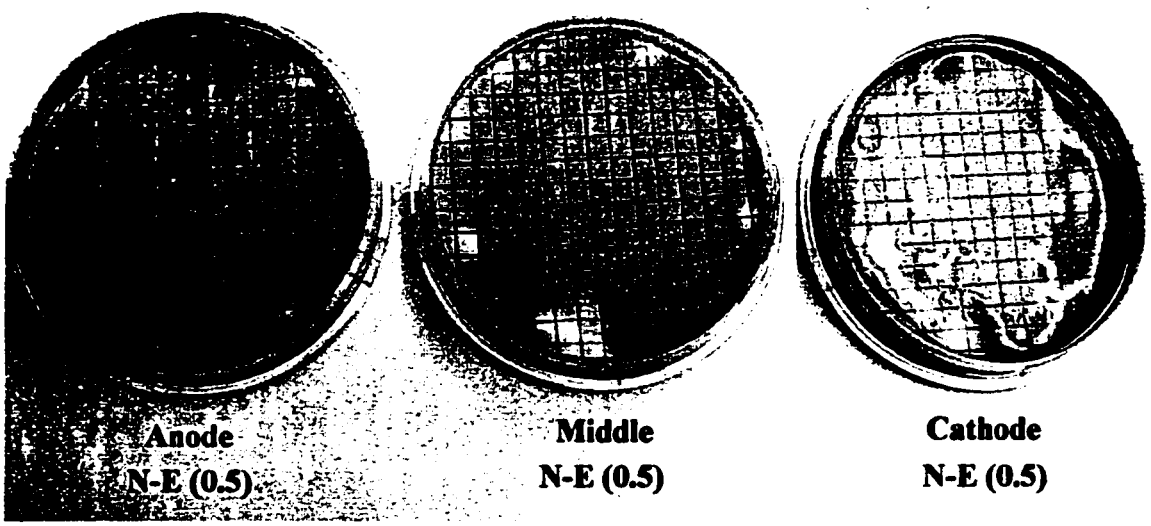


Figure A-3 Fecal coliform test results in cell #1 [N- E(0.5)]
(Anode, middle, and cathode)

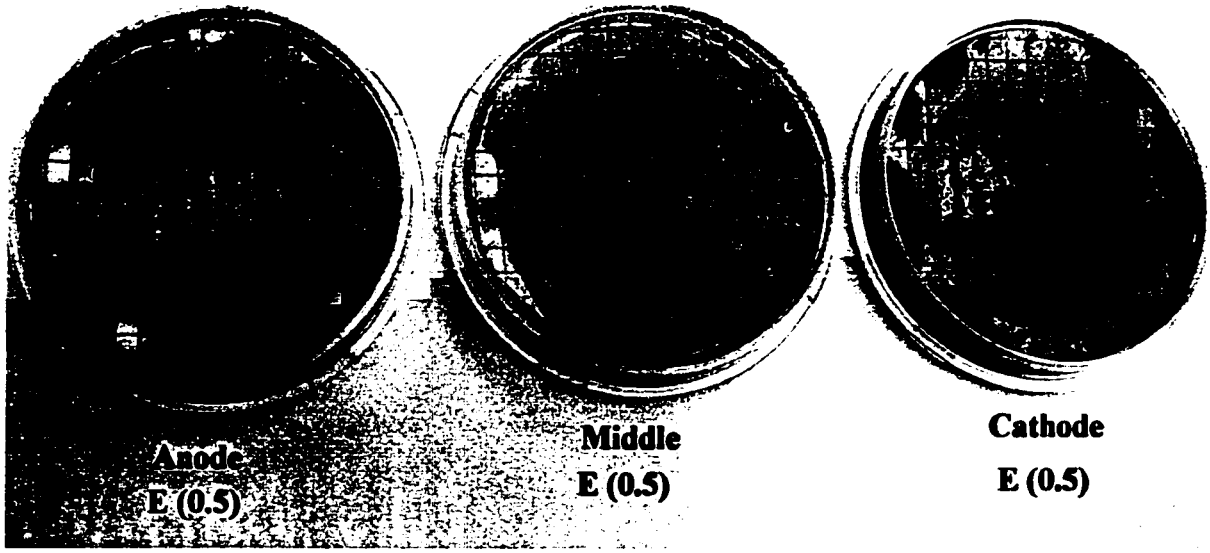


Figure A-4 Fecal coliform test results in cell #4 [E(0.5)]
(Anode, middle, and cathode)

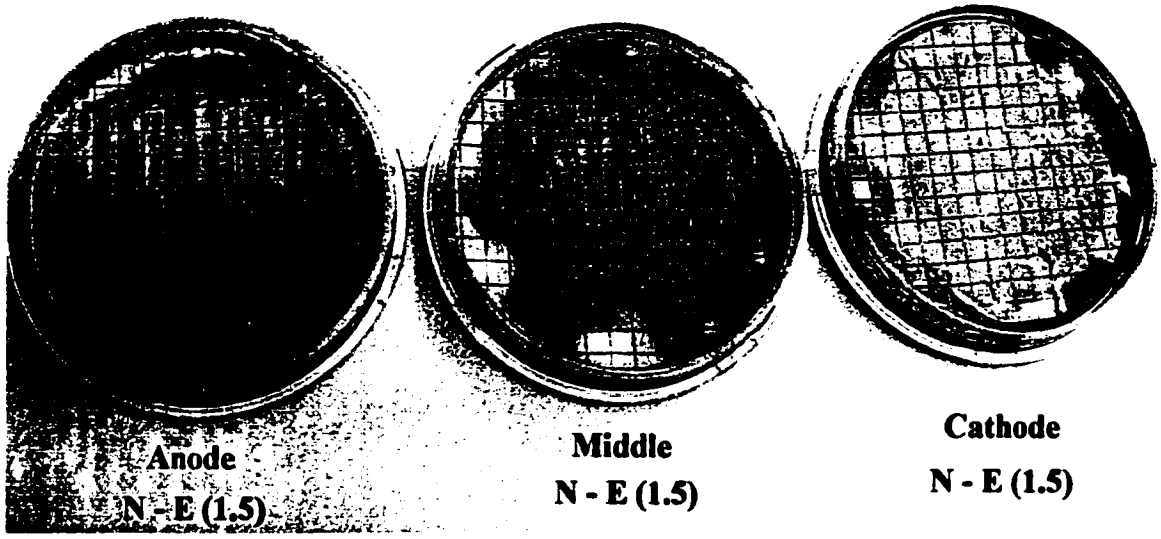


Figure A-5 Fecal coliform test results in cell #2 [N- E(1.5)]
(Anode, middle, and cathode)

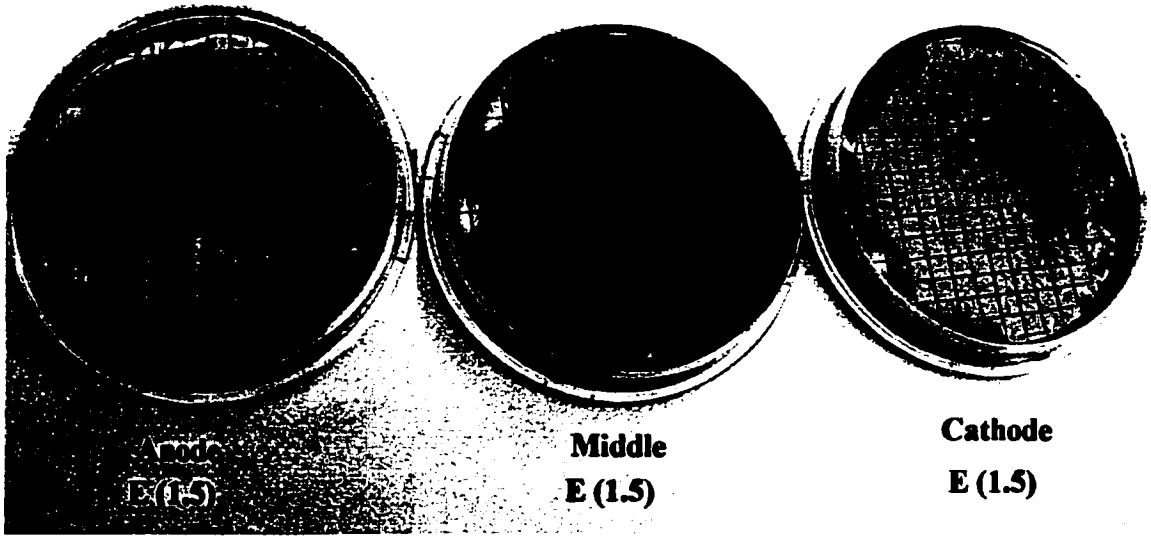


Figure A-6 Fecal coliform test results in cell #6 [E(1.5)]
(Anode, middle, and cathode)