Faculty of Engineering

COMPARISON OF KINETIC AND STATISTICAL MODELLING APPROACHES FOR CONTINUOUS ELECTROCOAGULATION FOR PEAT WATER TREATMENT DESIGN SIMULATION

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Bachelor of Engineering (Chemical Engineering) with Honours

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NUR SYAHIDA BINTI ABDUL JALAL

A dissertation submitted in partial fulfilment
of the requirement for the degree of
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Dedicated to my beloved parents, supervisor, and friends, who always bestow me with sustainable motivations and encouragement.

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ABSTRACT

In Sarawak, peat water is one of the potential raw water sources as a domestic water supply, particularly for the communities of the rural areas that do not have access to the municipal water supply. However, the peat water must be treated before it is used as a water supply due to the high acidity level and concentration of organic material. The previous study has proved that the electrocoagulation process is an effective treatment system to treat peat water due to its high-efficiency pollutant removal, environmentally friendly and low-cost technology. However, most of the electrocoagulation process studies are performed on a small scale or lab scale only. Hence, scaling up the electrocoagulation system must be considered to fully utilise the electrocoagulation treatment and meet the growing water demand, especially for rural communities. This research study aims to propose a continuous electrocoagulation peat water treatment design model for domestic usage in Sarawak rural areas where the design simulation development will adopt the most suitable and high accuracy model which is either kinetic or statistical models. Then, the respective model will be further used to simulate the electrocoagulation process for scaling up purposes. It is found that the variable order kinetic (VOK) model derived from the Freundlich isotherm results reveals good agreement between the simulated data and the experimental data compared to VOK-Langmuir and VOK-Jovanovic for kinetic modelling. This result indicates that the VOK-Freundlich model can predict the pollutant concentration at different treatment times by knowing the initial pollutant's concentration only. Besides, the predicted data obtained from the statistical model developed using Free Trial Design Expert 13 software by adopting Response Surface Methodology-Central Composite Design (RSM-CCD) is close to experimental data based on the coefficient of determination, R^2 and nonlinear chi-squared test, χ^2. Hence, the statistical model is the most suitable approach to simulate the continuous electrocoagulation system in treating peat water. In conclusion, the developed statistical model can be applied to other continuous electrocoagulation for peat water treatment design systems where the electrocoagulation process can be predicted with various operating parameters, which are treatment time and current supply, without conducting an actual experiment.

Keywords: Peat, Electrocoagulation, Kinetic Model, Adsorption Isotherm, Variable Order Kinetic (VOK), Statistical Model

ABSTRAK

Di Sarawak, air gambut merupakan salah satu sumber air mentah yang berpotensi sebagai bekalan air domestik, khususnya bagi masyarakat di kawasan luar bandar yang tidak mempunyai akses kepada bekalan air perbandaran. Walau bagaimanapun, air gambut mesti dirawat sebelum digunakan sebagai bekalan air kerana tahap keasidan dan kepekatan bahan organik yang tinggi. Kajian lepas telah membuktikan bahawa proses elektrokoagulasi adalah sistem rawatan yang berkesan untuk merawat air gambut kerana kecekapan tinggi penyingkiran bahan pencemar, mesra alam dan teknologi kos rendah. Namun begitu, kebanyakan proses kajian dijalankan hanya skala kecil atau skala makmal sahaja. Oleh itu, peningkatan skala elektrokoagulasi mesti dipertimbangkan untuk menggunakan sepenuhnya rawatan elektrokoagulasi dan memenuhi permintaan air yang semakin meningkat, terutamanya bagi masyarakat luar bandar. Tujuan kajian ini adalah untuk mencadangkan model untuk rawatan air gambut elektrokoagulasi berterusan untuk kegunaan domestik di kawasan luar bandar Sarawak di mana proses simulasi elektrokoagulasi air gambut ini akan mengguna pakai model yang paling sesuai dan berkejituan tinggi iaitu sama ada model kinetik atau statistik dimana model tersebut akan digunakan untuk tujuan penskalaan. Kajian ini mendapati model *Variable Order Kinetic (VOK)* yang diterbitkan dengan isoterma *Freundlich* adalah lebih sesuai berbanding *VOK-Langmui*r dan *VOK-Jovanovic* untuk pemodelan kinetik. Keputusan ini menunjukkan bahawa model *VOK-Freundlich* boleh meramal kuantiti bahan pencemar pada masa rawatan yang berbeza dengan mengetahui kuantiti awal sahaja. Selain itu, data ramalan yang diperoleh daripada model statistik yang dibuat menggunakan perisian *Free Trial Design Expert 13* dengan mengguna pakai *Response Surface Methodology-Central Composite Design (RSM-CCD)* adalah hampir dengan data eksperimen berdasarkan pekali penentuan, R^2 dan khi kuasa dua tak linear, $\chi 2$. Oleh itu, model statistik adalah pendekatan yang paling sesuai untuk mensimulasikan sistem elektrokoagulasi berterusan dalam merawat air gambut. Kesimpulannya, model statistik yang dibangunkan boleh digunakan untuk mensimulasi proses elektrokoagulasi yang lain untuk merawat air gambut di mana proses elektrokoagulasi boleh diramalkan dengan pelbagai parameter operasi, iaitu masa rawatan dan bekalan semasa, tanpa menjalankan eksperimen sebenar.

Kata kunci: Gambut, Elektrokoagulasi, Model Kinetik, Isoterma Penjerapan, Variable Order Kinetic (VOK), Model Statistik

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LIST OF ABBREVIATION

ANOVA	Analysis of Variance
BBD	Box -Behnken Design
CCD	Central Composite Design
COD	Chemical Oxygen Demand
RSM	Response Surface Methodology
SA/V	Surface Area of Electrode to Solution's Volume
TSS	Total Suspended Solid
VOK	Variable Order Kinetic
WHO	World Health Organisation

LIST OF NOMENCLATURE

%	Percentage
χ^2	chi-squared
A	Ampere
$Al(OH)_3$	Aluminium Hydroxide
L	litre
L/g	litre per gram
mg/g	milligram per gram
mg/L	milligram per litre
min	minutes
R^2	Coefficient of determination
s	seconds

CHAPTER 1
INTRODUCTION

1.1 Overview

This chapter introduces the background of the research project comprised of four parts, (i) domestic water, (ii) peat water, (iii) electrocoagulation, and (iv) process modelling and simulation. This chapter also covers the research problems, scopes, main aim, objectives, methodology, and expected outcomes.

1.2 Domestic Water

According to Boretti and Rosa (2019), domestic water usage currently accounts for 10% of the total global water use, and it is estimated that demand will increase drastically from 2010 to 2050 in every region except for Western Europe. A significant increment in domestic water demand is expected to occur in Africa and Asia due to the increase in municipal water supply in the urban area (Wada et al., 2015). In Malaysia, the rise of water demand in industrial and domestic sectors, nearly twofold since the 2000s, aims to sustain the growth of the human population and industrialisation (Anang et al., 2019). Additionally, Malaysia is categorised as one of the high-rank countries in terms of domestic water consumption since the domestic water consumption exceeds the suggested target by the World Health Organisation (WHO), as reported by Hafizi Md Lani et al. (2018). **Figure 1.1** shows Malaysia's domestic water consumption in litres per day from 2009 until 2016 and the allowable limit by WHO. From **Figure 1.1**, the graph shows a fluctuating trend in water consumption, but it is high each year, indicating that the demand for domestic water consumption in Malaysia is high.

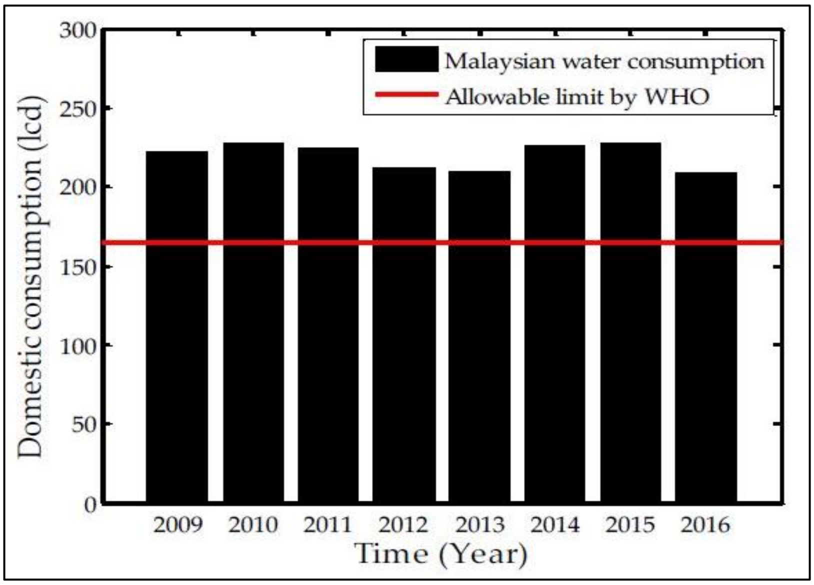

Figure 1.1: Domestic water consumption in Malaysia from 2009 to 2016 (Hafizi Md Lani et al., 2018)

In Sarawak, approximately 60% of the population lives in rural areas and small groups, which are scattered throughout the entire state (Memon, 1999). According to Shakeran (2004), the water sources utilised by the people living in urban areas differ from the rural communities, where the raw water sources in the urban areas originate from major river basins. In contrast, the rural communities utilised the gravity-feed water catchment, and the freshwater supply comes from smaller water catchments. According to Abdul Rahman et al. (2020b), peat water is one of the potential raw water sources as domestic water supply, particularly for the communities of rural areas that do not have access to the municipal water supply. However, the peat water must be treated before being used as a water supply due to the high level of acidity and organic material concentration. (Syafalni et al., 2013).

1.3 Peat Water

Peatland can be defined as the surface organic layer of soil consisting of partially decomposed organic matter derived mainly from plant material. An international chart of total peat deposits across the country has stated that Malaysia is ranked as the 9th state with the highest total area of peat soil (Adon et al., 2012). Ministry of Natural Resources and Environment Malaysia (2011) stated in National Action Plan for Peatland programme that peatland plays a vital role in some areas in Malaysia as it acts as a natural reservoir. In addition, the peatland will absorb, trap, and store water during heavy rainfall and this associated water is known as peat water. According to Mutalib (1992), Malaysia has approximately 2.6 million hectares of peatlands, where more than 70% of the peatland is in Sarawak. The freshwater peat covers about 1.698 million ha of Sarawak's overall state land area, which is 12.4 million ha, while the mangrove area covers approximately 154,000 hectares (Department Of Irrigation & Drainage Sarawak, 2016). Generally, peat soil in Sarawak usually being found within the delta and stretches inland along the riverine of the Samarahan-Sadong, Lupar-Saribas, Rajang, Baram and Limbang river system. **Figure 1.2** shows the distribution of peat soil in Sarawak.

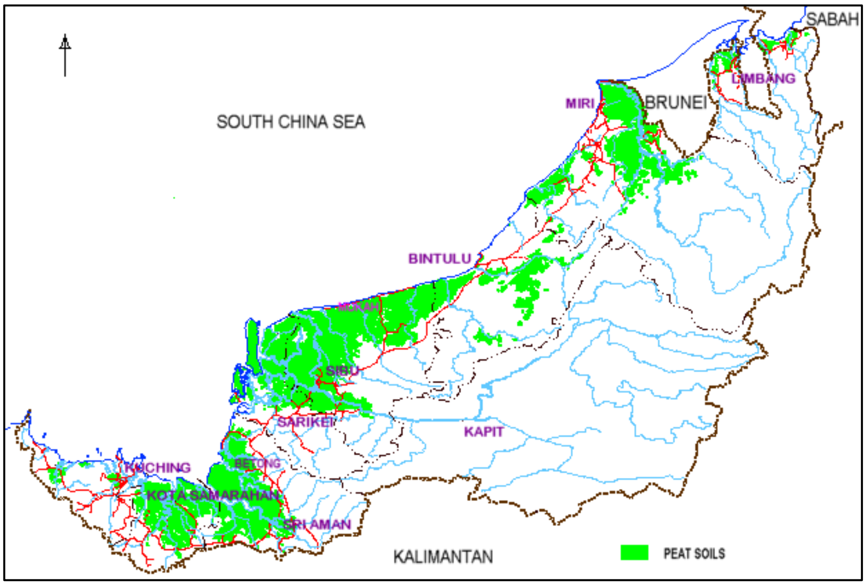

Figure 1.2: Distribution of peat soil in Sarawak (Department of Irrigation and Drainage Sarawak, 2016)

Peat is formed when the biomass production rate from adapted vegetation such as mangroves and swamp forests is higher than the decomposition rate due to the presence of a permanently high-water table. As a result, the aerobic decomposition of the plant debris is halted (Mutert et al., 1999). According to Noraini et al. (2010), humic acid is one of the main components of peat water derived from lignin decomposition. It is a principle of colouring matter to the peat water, specifically brown colour. As a result, the colour of the water in the peat swamp is typically dark brown to black due to the water contact with organic material from different stages of peat decomposition, including humic acid. Hence, the peat water must be treated due to the acidity and tremendous amount of organic material, making it unsuitable for consumption, especially for the rural communities that live in peat swamps and have difficulty accessing clean water (Syafalni et al., 2013).

1.4 Electrocoagulation

Electrocoagulation is one of the water treatment methods that applies an electrochemical reaction that simultaneously removes suspended solids, heavy metals and other contaminants by utilising electric current instead of chemical reagents. According to Zulfikar et al. (2013), various approaches have been developed to remove the humic acid as the main component from peat water, where electrocoagulation is one of the methods. The electrocoagulation process is proven to be a cost-effective technology that is able to treat peat water with a high removal efficiency of particulate at a small treatment facility (Abdul Rahman et al., 2021a).

The electrocoagulation system consists of a tank with an anode and a cathode that is made of metal plates and connected to a power supply. According to Ozyonar and Karagozoglu (2011), aluminium and iron are usually used as electrode materials and commonly consist of the same or different materials. Generally, the basic principle of electrocoagulation is the oxidation of anode and cathode reduction reactions that occurs simultaneously. During the electrocoagulation process, the metal ions are generated in situ by the dissolution of the sacrificial anode (Sen et al., 2019). The generated metal ion then binds with the negatively charged ion released, OH^- produced from the cathode's reduction reaction and forms metal hydroxide. These metal hydroxide ions will act as a coagulant, and the soluble or colloidal pollutants will adsorb on the coagulant surface (Ozyonar & Karagozoglu, 2011). Then, the formation of the hydroxide complex ions neutralises the surface charge on the pollutants, thereby allowing them to agglomerate and form floc. The floc sediment at the bottom of the reactor tank can be discarded and removed through filtration process. **Equation 1.1** and **Equation 1.2** illustrate the electrocoagulation reaction occurring at the anode and cathode of the aluminium electrode as an example.

$$\text{At the anode: } Al \rightarrow Al_{(aq)}^{+3} + 3e^- \quad \textbf{(1.1)}$$

$$\text{At the cathode: } 3H_2O + 3e^- \rightarrow \frac{3}{2}H_{2(g)} + 3OH^- \quad \textbf{(1.2)}$$

1.5 Process Modelling and Simulation

The purpose of a model in engineering scope is to convey design information, simulate and specify a process. The adsorption kinetic model describes the adsorption mechanisms, which can determine the time taken needed to reach equilibrium for the adsorption process (Sahoo & Prelot, 2020). In electrocoagulation process, the pollutant is generally adsorbed at the metal hydroxide surface, effectively removing the pollutant from the raw water. As such, adsorption kinetic modelling can be used to estimate the amount of coagulant produced for a given time as well as pollutant removal since the pollutant removal can be modelled using an adsorption phenomenon (Benaissa et al., 2016).

According to Zailani and Zin (2018), various factors affect the efficiency of the electrocoagulation process, including treatment time, current density, number of electrodes, size of electrodes, pH of the water sample, and addition of supporting electrolytes. Running one factor to observe the influence of the electrocoagulation operational parameters at a time experiment required many experiments run. Hence, the single factor varying experiments are time-consuming and difficult to conduct (Yuangyai & Nembhard, 2010). Besides, the interactions between each factor and their combined effect on the responses cannot be determined in a fast way by running the experiment. Therefore, a statistical model is one of the solutions to counter the drawbacks that arise in the conventional method where the statistical model able to determine the interaction between each factor (Kamal & Kumar, 2021). Generally, statistical modelling is a mathematical model that uses statistical assumptions to describe the data generation and predict the actual system behaviour.

Process simulation is a model-based representation of a process, including chemical, physical, biological, using computer-based modelling to understand the system's behaviour and predict the effect of changes (Ghasem, 2021). An abundance of research has focused on studying the electrocoagulation process, especially on the effectiveness of removing pollutants using this method. Additionally, several research studies have also analysed the effect of various parameters, such as the size and distance of the electrode plate, treatment time, current density, etc., on the electrocoagulation performance. However, the challenge of developing and researching the model and the automation of the electrocoagulation process has arisen (Safonyk et al., 2019b). **Table**

1.1 shows a list of the research study on peat water treatment using electrocoagulation, where most of the studies focus on studying the treatment method feasibility and on a lab scale only.

Table 1.1: List of research studies on peat water treatment using electrocoagulation

No.	Research Title	Author	Findings
1	Peat Water Treatment by Electrocoagulation using Aluminium Electrodes	(Bow & Dewi, 2019)	Factors that affect the electrocoagulation performance in removing the pollutants contained in the peat water by using an aluminium electrode, including current density and treatment time.
2	Kinetic Study & Statistical Modelling of Sarawak Peat Water Electrocoagulation System using Copper and Aluminium Electrodes	(Abdul Rahman et al., 2020a)	Conduct kinetic study and statistical analysis for batch and continuous electrocoagulation processes of peat water treatment in Sarawak using aluminium and copper electrodes.
3	Batch Electrocoagulation Treatment of Peat Water in Sarawak with Galvanized Iron Electrodes	(Abdul Rahman et al., 2020b)	Study the effects of the interelectrode distance, applied current density, number of electrodes, and treatment time on peat water in a batch electrocoagulation system.
4	Experimental Studies on Continuous Electrocoagulation Treatment of Peat Water in Sarawak with Copper Electrodes	(Abdul Rahman et al., 2021b)	Fabricate a continuous electrocoagulation water treatment system using copper electrodes to treat peat water in Sarawak.

Scale-up of a reactor or a system is a part of the process simulation. It is important to scale up the electrocoagulation system in order to implement the actual peat water treatment system in rural areas. The scale-up of a batch electrocoagulation system will be utilised as a portable electrocoagulation system for household usage. Meanwhile, a continuous electrocoagulation system will become a centralised system where residents can collect the water within that place (Abdul Rahman et al., 2020a). According to

Innovation (2020), modelling and simulation support the process of scale-up from lab to plant. As such, kinetic and statistical modelling development is essential as these models aid in simulation and scale-up purposes.

1.6 Research Problems

Ogilvy (2017) reported that approximately 39% of rural area houses in Sarawak experienced water scarcity and have yet to access a reliable water supply. Inadequate clean water supply for the rural communities has become a major concern as it threatens their health and development. As a result, the shortage of clean water urges the communities living in peat areas to be forced to utilise peat water as their alternative water resource for domestic usage (Abdul Rahman et al., 2020a). However, peat water is not suitable for direct use because it has a high acidity level, organic matter level, iron (Fe) and manganese (Mn), where extensive treatment is required before it reaches the quality standard (Bow & Dewi, 2019).

According to Elazzouzi et al. (2017), the electrocoagulation technology is widely used in various processes to treat wastewater due to its several advantages, such as low operating cost at removing particulates, the coagulants directly electrogenerated, and more effective and rapid organic matter separation than in coagulation. Several research studies have been conducted to prove the efficiency and feasibility of the electrocoagulation process in reducing the several contaminants in peat water (Abdul Rahman et al., 2020b). However, most of the electrocoagulation process studies are performed on a small scale or lab-scale only. Thus, scaling up the electrocoagulation system must be considered to fully utilise the electrochemical wastewater treatment method and meet the growing water demand, especially for rural areas. According to (Safonyk et al., 2019a), the design of the simulation of the electrocoagulation treatment allows the electrocoagulation behaviour can be predicted and studied easily over a long period of time. Additionally, the development of the design simulation serves as an important method of analysing the detailed design of the continuous electrocoagulation system with various design parameters prior to constructing the actual water treatment. Westbrook and Curran (2019) also stated that modelling chemical reaction systems provide fundamental information for chemical process design and optimisation. As such, the design simulations based on the developed model make it possible to scale up and optimise the electrocoagulation system relatively fast based on the requirements.