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DEVELOPMENT OF ELECTROLYZED WATER SANITATION PROGRAM FOR SME FROZEN MEAT PATTY INDUSTRY

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DEVELOPMENT OF ELECTROLYZED WATER SANITATION PROGRAM FOR SME FROZEN MEAT PATTY INDUSTRY

By

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Faculty : Engineering

Sanitation (a process of cleaning and disinfection) of food contact surfaces is an essential procedure in the frozen meat industry. In all countries, sanitation is mandatory in the food industry to ensure food safety throughout the production processes as prescribed by their food law. Implementing a suitable sanitation program (depending on the size and complexity of the food processing) is part of the general pre-requisite for food safety management. Meeting relevant legislation requirement for sanitation is important for compliance reasons; it is also beneficial to the success of the food business. Implementation of an effective sanitation program can maintain a clean work environment and produce high-quality and safe food products. The frozen meat industries, especially Small and Medium Enterprises (SMEs), are facing difficulties in implementing a good sanitation program. Budget restriction, limited production area, and lack of knowledge on the latest and effective sanitation technology (either cleaning tools or sanitation solutions) are the hurdles for sanitation efforts. Suitable cleaning tools and food-grade sanitation solutions are expensive and can burden Food SMEs. Therefore, the development of innovative green sanitation may result in cost savings and the elimination of harsh chemicals used in the food factory. Electrolyzed water (EW) is classified as a green sanitation solution. The main objective of this work is to propose a green sanitation technology based on industrial-based and laboratory-based studies which can be implemented in the frozen meat industry. The study was initiated with evaluation studies of the current sanitation program at a local SME factory (Factory X) that produces frozen meat patty. To evaluate the factory's sanitation process, interviews with the top-to-bottom workers and several visits were conducted. In particular, the purpose was to determine current cleaning tools, sanitation solutions, sanitation steps/procedures used, and problems faced by Factory X. In designing a good sanitation program, several factors were considered: 1) cleaning tools, 2) sanitation parameters (time, temperature, and water jet pressure), and 3) sanitation solutions. Several sanitation programs were tested using a portable cleaning unit and industrial cleaning brushes. The efficiency of the portable cleaning unit at different nozzle distances (10 cm and 20 cm), sanitation times (30 s and 120 s), and temperatures (20°C and 65°C) in reducing different foodborne pathogens (*Escherichia coli*, *Listeria monocytogenes,* and *Salmonella enteritidis*) were evaluated. A preliminary study has revealed that using a portable cleaning unit was not a cost-effective solution due to commercial sanitation solutions and heating costs. Accordingly, new technology was proposed to integrate an EW generator into the cleaning unit. The optimum electrolyzing parameters of acidic electrolyzed water (AcEW) and alkaline electrolyzed water (AlEW) were investigated using Box–Behnken experimental design. The tests were conducted at different types of electrodes (titanium, zinc, copper, and stainless steel), electrical voltages (5, 10, and 15 V), electrolysis times (5, 7.5, and 10 minutes), and NaCl concentrations (0.05, 0.53, and 1.0%). There were no obvious differences observed in the physicochemical properties of EW when different electrodes were used. However, stainless steel was chosen as it meets most of the selection criteria. The best-optimized conditions for AcEW were at 11.39 V, 0.65% NaCl, and 7.23 min, while the best-optimized conditions for AlEW were at 10.32 V, 0.6% NaCl, and 7.49 min. The bactericidal activity of AcEW and AlEW were examined against *Escherichia coli* ATCC 10536 at different temperatures (30°C and 50°C) for 30 s. The capability of both EWs (AcEW and AlEW) to clean stainless steel surfaces inoculated with *Escherichia coli* ATCC 10536 (with and without the presence of fat-based residue) was also assessed. The results show that both EWs can reduce *Escherichia coli* to non-detectable levels (less than 2 log CFU/ml). However, EW could not physically, and microbiologically clean the plates, which were fouled with inoculated fat-based residues, as the deposits acted as a barrier and it reduced efficacy. Thus, mechanical action (manual brushing or shear stress from rinsing effect) and hot water rinse were included in the pre-rinse steps to remove fat-based residues and ensure the surfaces were ready for the next sanitation steps (alkaline wash, acidic wash, or disinfection). A conceptual design of a portable electrolysis sanitation unit was designed based on the optimized electrolyzing parameters and the proposed sanitation program. The theory of Inventive Problem Solving (TRIZ), a systematic methodology for innovation, was applied to get the creative conceptual design ideas for the portable electrolysis sanitation unit. The portable electrolysis sanitation unit has 2 main systems: 1) electrolyzed water generation system and 2) heating and water jet system. The portable electrolysis sanitation unit can generate hot water at different water jet pressure and, at the same time, can generate AcEW and AlEW that will replace commercial sanitation solutions. Industrial-based studies using a portable cleaning unit have shown promising results and the proposed sanitation program has improved sanitation efficiency significantly. It is expected that the developed conceptual design of the portable electrolysis sanitation unit could bring more benefit to the frozen meat patty industry by reducing sanitation costs and addressing numerous sanitation issues.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN PROGRAM SANITASI AIR ELEKTROLISIS UNTUK INDUSTRI DAGING SEJUK BEKU

Oleh

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Abstrak Sanitasi (proses pembersihan dan disinfeksi) di permukaan sentuhan makanan adalah prosedur yang penting dalam industri daging sejuk beku. Di semua negara, sanitasi adalah wajib dalam industri makanan untuk memastikan keselamatan makanan sepanjang proses pengeluaran seperti yang ditetapkan oleh undang-undang makanan mereka. Perlaksanaan program sanitasi yang sesuai (bergantung kepada saiz dan kerumitan pemprosesan makanan) adalah sebahagian daripada prasyarat am untuk pengurusan keselamatan makanan. Memenuhi keperluan undang-undang yang berkaitan dengan sanitasi adalah penting atas sebab faktor pematuhan; ia juga memberi manfaat kepada kejayaan perniagaan makanan. Pelaksanaan program sanitasi yang berkesan dapat mengekalkan persekitaran kerja yang bersih dan menghasilkan produk makanan yang berkualiti tinggi dan selamat. Industri daging sejuk beku khususnya Perusahaan Kecil dan Sederhana (PKS) menghadapi kesukaran untuk melaksanakan program sanitasi yang baik. Sekatan belanjawan, kawasan pengeluaran yang terhad, dan kekurangan pengetahuan berkenaan teknologi sanitasi yang terkini dan berkesan (sama ada perkakasan pembersih atau larutan sanitasi) adalah halangan untuk usaha perlaksanaan program sanitasi. Perkakasan pembersih yang sesuai dan larutan sanitasi yang bergred makanan adalah mahal dan ini boleh membebankan PKS yang mengeluarkan produk makanan. Oleh itu, pembangunan sanitasi hijau yang inovatif dapat menjimatkan kos dan mengelak penggunaan bahan kimia yang berbahaya di kilang makanan. Air elektrolisis (AE) diklasifikasikan sebagai salah satu penyelesaian untuk sanitasi hijau. Objektif utama kajian ini adalah untuk mencadangkan teknologi sanitasi hijau, berdasarkan kajian berasaskan industri dan kajian berasaskan makmal yang boleh dilaksanakan di industri daging sejuk beku. Kajian ini dimulakan dengan kajian penilaian terhadap program sanitasi semasa di sebuah kilang PKS tempatan (Kilang X), yang menghasilkan patti daging sejuk beku. Temu ramah dengan pekerja daripada peringkat atas ke bawah dan beberapa lawatan yang telah diadakan bagi menilai proses sanitasi di kilang. Tujuan khususnya adalah untuk mengenal pasti perkakasan pembersih semasa, larutan

sanitasi semasa, langkah/prosedur sanitasi semasa, dan masalah sanitasi yang dihadapi oleh Kilang X. Untuk mereka bentuk program sanitasi yang baik, ada beberapa faktor yang perlu dipertimbangkan: 1) perkakas pembersih, 2) parameter sanitasi (masa, suhu, dan tekanan jet air), dan 3) larutan sanitasi. Beberapa program sanitasi telah diuji dengan menggunakan unit pembersih mudah alih dan berus pembersih industri. Kesan unit pembersih mudah alih dengan jarak muncung yang berbeza (10 cm dan 20 cm), masa pembersihan (30 s dan 120 s), dan suhu (20°C dan 65°C) dalam mengurangkan pelbagai patogen bawaan makanan (*Escherichia coli*, *Listeria monocytogenes*, dan *Salmonella enteritidis*) telah dinilai. Hasil dari kajian awal menunjukkan bahawa penggunaan unit pembersih mudah alih sahaja tidak mencukupi untuk dianggap sebagai penyelesaian yang menjimatkan kos kerana kos pembersihan bahan kimia dan kos pemanasan yang masih tinggi. Oleh itu, teknologi baru yang menggabungkan unit pembersih mudah alih dan penjana air elektrolisis telah dicadangkan. Parameter elektrolisis yang optimum bagi air elektrolisis berasid (AEBS) dan air elektrolisis beralkali (AEBL) diselidik dengan menggunakan reka bentuk eksperimental Box–Behnken. Ujian dilakukan dengan pelbagai jenis elektrod (titanium, zink, tembaga, dan keluli kalis karat), voltan elektrik (5, 10, dan 15 V), masa elektrolisis (5, 7.5, dan 10 minit), dan kepekatan NaCl (0.05, 0.53, dan 1.0%). Tidak ada perbezaan yang jelas yang diperhatikan dalam sifat fizikokimia AE ketika elektrod yang berbeza digunakan. Walau bagaimanapun, keluli kalis karat dipilih kerana memenuhi kebanyakan kriteria pemilihan. Keadaan yang optimum terbaik untuk AEBS adalah pada 11.39 V, 0.65% NaCl, dan 7.23 min, sementara keadaan yang optimum terbaik untuk AEBL adalah pada 10.32 V, 0.6% NaCl, dan 7.49 min. Aktiviti bakterisidal AEBS dan AEBL telah diperiksa terhadap *Escherichia coli* ATCC 10536 pada suhu yang berbeza (30°C dan 50°C) selama 30 s. AE juga dinilai dari segi kemampuannya untuk membersihkan permukaan kupon keluli kalis karat yang diinokulasi dengan *Escherichia coli* ATCC 10536 (dengan dan tanpa kehadiran sisa berasaskan lemak). Hasil kajian menunjukkan bahawa kedua-dua AE memiliki kebolehan untuk menurunkan kadar *Escherichia coli* ke tahap yang tidak dapat dikesan (kurang dari 2 log CFU/ml). Walau bagaimanapun, AE tidak dapat membersihkan kupon yang dikotorkan dengan sisa berasaskan lemak yang diinokulasi sehingga ke tahap fizikal dan mikrobiologi yang mencukupi kerana sisa berasaskan lemak bertindak sebagai penghalang yang mengurangkan keberkesanan AE. Oleh itu, tindakan mekanikal (berus secara manual atau tekanan ricih dari kesan pembilasan) dan pembilasan air panas adalah sangat penting semasa langkah pra-bilas untuk membuang sisa berasaskan lemak dan untuk memastikan permukaannya bersedia untuk langkah sanitasi seterusnya (pencucian beralkali, pencucian berasid, atau disinfeksi). Reka bentuk konseptual bagi unit sanitasi elektrolisis mudah alih direka berdasarkan parameter elektrolisis yang optimum dan program sanitasi yang dicadangkan. Teori Penyelesaian Masalah Inventif (TRIZ), adalah metodologi sistematik untuk inovasi, telah digunakan untuk mendapatkan idea reka bentuk konseptual yang kreatif untuk unit sanitasi elektrolisis mudah alih. Unit sanitasi elektrolisis mudah alih mempunyai 2 sistem utama: 1) sistem penjanaan air elektrolisis dan 2) sistem pemanas dan jet air. Unit sanitasi elektrolisis mudah alih dapat menghasilkan air panas pada tekanan jet air yang berbeza dan, pada masa yang sama akan dapat menghasilkan AEBS dan AEBL, yang akan menggantikan larutan sanitasi komersial. Kajian berasaskan industri menggunakan unit pembersihan mudah alih telah menunjukkan hasil yang memberangsangkan dan program sanitasi yang dicadangkan telah meningkatkan kecekapan sanitasi dengan ketara. Dijangkakan reka bentuk konseptual yang dibangunkan bagi unit sanitasi elektrolisis mudah alih boleh membawa lebih banyak manfaat kepada industri industri patti daging sejuk beku dengan mengurangkan kos sanitasi dan menangani pelbagai isu sanitasi.

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LIST OF ABBREVIATIONS

EW	Electrolyzed water
AcEW	Acidic electrolyzed water
AlEW	Alkaline electrolyzed water
NEW	Neutral electrolyzed water
sAcEW	Slightly acidic electrolyzed water
SAcEW	Strongly acidic electrolyzed water
SAlEW	Strongly alkaline electrolyzed water
ACC	Available chlorine concentration
DO	Dissolved oxygen
RSM	Response surface method
FOG	Fat, oil, and grease
ATP	Adenosine Triphosphate
SMEs	Small-medium enterprises
SME	Small-medium enterprise
GMP	Good Manufacturing Practice
NaOH	Sodium hydroxide
NaCl	Sodium chloride
H_2O_2	Hydrogen peroxide
O_3	Ozone
HOCl	Hypochlorous acid
HCl	Hyphochloric acid
NaClO	Sodium hypochlorite
BT	Before treatment
CV	Control variables

MV	Manipulated variable
H	Hypothesis
t_e	Electrolysis time
TRIZ	Theory of Inventive Problem Solving
SS	Stainless steel
DOF	Degree of freedom

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Food safety is a top priority in all food industries (e.g., meat processing, fruits and vegetables, confectionaries, and beverages) as it is directly associated with consumers' health. A proper plant sanitation system is essential for maintaining the facility's hygiene level (Goode et al., 2013). The system is intended to remove all visible residues and minimize microorganisms to safe levels (Tamime, 2008). Foodborne illnesses caused by foodborne pathogens (e.g., *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes*) can be prevented by ensuring cleanliness (physically, chemically, and microbiologically clean) of the equipment surfaces.

Sanitation (i.e., cleaning and disinfection) is a common term in North America, while it is known as hygiene in Europe (Shapton & Shapton, 1993). Cleaning is the removal of soil/residue from surfaces by physical, chemical, and mechanical means. Disinfection is defined as the inactivation and destruction of vegetative cells (except spores) on surfaces to reduce harmful microorganisms. Sanitizing involves reducing the number of bacteria on a surface to a level considered safe for public health. A disinfectant (i.e., sanitizing solution) is weaker than a disinfectant (i.e., disinfection solution). Sterilization is defined as the destruction or elimination of all microbial life (fungi, viruses, bacteria, and spores). Sterilizing is not suitable for some food plants as it uses a high temperature of more than 100ºC (Stanga, 2010).

Large food manufacturers do not have complicated hygienic concerns as their research and development teams are continuously discovering and developing advanced and efficient sanitation systems. Moreover, they have a well-designed plant layout (certified with Good Manufacturing Practice (GMP)) that allows the sanitation process to run smoothly (Goode et al., 2013; Khalid et al., 2016). A good sanitation program will lead to a better quality of products, safer working environments for workers, and longer food processing equipment durability. A good selection of sanitation solutions and cleaning tools (e.g., water jet, cleaning brushes, and sponge) will contribute to an effective sanitation program. The program is mandatory in the food industry to ensure food safety throughout production processes (Regulation 9: Food safety assurance program, Food Hygiene Regulation 2009, regulation enacted according to Section 34 of Food Act 1983).

Despite their importance, the sanitation programs have received little attention in small-medium enterprises (SMEs) as they do not generate a profit. Most

Malaysian SMEs factories do not fulfill GMP requirements and the unsystematic or unorganized plant layout makes implementing a good sanitation program more challenging (Noor Hasnan et al., 2014). Besides, the high cost of food-grade solutions or chemicals is a burden for SMEs. Due to the circumstances, SMEs manufacturers tend to ignore the importance of investing in sanitation programs. Moreover, sanitation can be a complex and costly operation from SMEs' perspective (Khalid et al., 2016; Köhler et al., 2015; Noor Hasnan et al., 2014), thus they opted to focus on productivity. The sanitation costs may include the costs of sanitation solutions, energy consumption to heat up and pump the sanitation solutions, production loss, plant downtime, and wastewater treatment (Bird and Espig, 1994; Khalid et al., 2016). For instance, in the brewery industry, the costs for water used as sanitation solutions can vary between 0.19 €/m^3 and 2.30 €/m^3 (Köhler et al., 2015). Khalid et al. (2016) has shown that the costs for sanitation solutions (2.0 wt.% NaOH) can consume up to 58% of the total sanitation costs for pink guava puree (PGP) residue removal. Another issue in SMEs is the difficulty to maintain good food hygiene practices due to lack of knowledge and shortage of skilled human capital resources (due to high turnover of staff and lack of training) (Noor Hasnan et al., 2014). Studies performed by Ismail et al. (2016) and Abdul-Mutalib et al. (2012) revealed that food manufacturers in Malaysia are well aware of the importance of sanitation in food factories and the influence of food hygiene on health and living. However, several of them are taking the issue lightly, which leads to increased food poisoning cases.

According to the Department of Statistics Malaysia, 16,583 foodborne diseases were reported in Malaysia in 2019 (with a 32.5 million population) (Mahidin, 2020a, 2020b). World Health Organization (WHO) (1992) reported that 25% of foodborne outbreaks are closely associated with cross-contamination events which include contaminated equipment, deficient hygiene practice, contamination via food handlers, processing, or inadequate storage (Carrasco et al., 2012). Contaminated equipment is the result of a poor sanitation program. A physical, chemical, or microbiological contaminant can jeopardize food products' safety, appearance, and quality (Ismail et al., 2016; Tamime, 2008). In 2021, several food factories were ordered to close for two weeks by the Department of Environmental Health, Food Safety, and Quality, Malaysia due to hygienic issues. These factories failed to meet the stipulated standard on cleanliness and were found to operate in unhygienic conditions. Failure to meet the prescribed standard can cause contamination and food poisoning. The temporary closure order was made under Section 11 of the Food Act 1983, adding that the manufacturers must clean their factories before being allowed to operate. Several compound notices amounted to RM 3000 – RM 12 000 were issued (Bernama, 2021a, 2021b; Hilmy, 2021). Food premises that fail to comply with Food Hygiene Regulation 2009 are liable to a fine not exceeding RM 10 000 or a sentence not exceeding two years imprisonment. A specially designed sanitation program is needed for every SME to fulfill hygienic and economic requirements (Wilson, 2005). Companies can continuously maintain a hygienic factory environment when a standard operating procedure for sanitation programs has been established (Wilson, 2005).

Sanitation is mandatory in the food industry to maintain safe food production (Regulation 15: Cleanliness of food premises, Food Hygiene Regulation 2009, regulation enacted according to Section 34 of Food Act 1983). As a result, daily sanitation is necessary for food production areas. However, this practice has several drawbacks: high costs, excessive water usage, hazardous chemical effluents, and chemical residue in processing equipment, which may compromise food safety and quality. Hence, concerned food producers and consumers are now demanding green sanitation solutions. Green sanitation entails utilizing environmentally friendly sanitation solutions that do not emit pollutants.

The demand for environmentally friendly cleaning solutions, often known as green sanitation solutions, kept increasing every. An excellent green sanitation solution can 1) eliminate the use of harsh chemicals in the plant, 2) avoid an extensive rinsing process, and 3) provide greater convenience in obtaining sanitation solutions (i.e., on-site generation).

1.2 Problem statement

An inexpensive yet effective sanitation solution is needed to establish a good sanitation program. A food-grade sanitation solution is rinsible and causes less harm (less corrosive and less disruptive) to the food-contact surfaces. However, the high price of the sanitation solution becomes a hindrance, especially for food SMEs. Bulk sanitation solution purchases are common to reduce the cost per bottle. However, bulk purchasing can lead to several problems, including a crowded and improper sanitation solution storage area. Due to limited sanitation solution storage, SMEs store excess sanitation solutions in inappropriate spaces such as the hall, inside the dry raw materials area, and outside the factory. There are times when the sanitation solutions have exceeded their expiration date. This led to another problem; more storage space was required for unopened and expired sanitation solutions. Some SMEs will just use the expired sanitation solution. In the worst-case scenario, the expired sanitation solution is improperly disposed of because chemical disposal services are expensive. Furthermore, most food SMEs facilities are not equipped with water treatment facilities. A basic water treatment facility treats water leaving the factory to meet federal discharge limits. It is strongly needed if chemical-based detergents and disinfectants are used. Unfortunately, most food SMEs are unable to have their own water treatment facility due to cost and limited factory space.

Another issue in food SMEs is the selection of suitable and effective cleaning tools. Food SMEs manufacturers do not know how to use appropriate cleaning tools (e.g., water jets, brushes, sponges, sweepers, and floor squeegees). The water jet helps clean difficult-to-clean areas such as uneven surfaces or the edges of food processing equipment. However, SMEs presume that all the food-grade cleaning tools are expensive, so they avoid using them. Food-grade cleaning tools are more durable and can be used for a very long period as compared to common cleaning tools. SMEs prefer simple and easy to operate cleaning tools because they have average-skilled workers and a high turnover rate. The high turnover of staff makes sanitation training impossible. Sanitation training takes time and energy. Thus, they often skip it and assume that the workers will eventually learn after working for a while. Based on these issues, it is evident that there is a need to design a portable electrolysis sanitation unit with multiple functions (generation of hot water and sanitation solution). The completion of this unit will greatly benefit food SMEs.

Nowadays, most industries are looking for a sustainable solution in managing their production operation. Improving the sanitation process is one of the industries' targets, such as reducing commercial sanitation solution usage. Electrolyzed water (EW) has been claimed as a green sanitation solution as it can be used as either a cleaning or disinfection solution. Besides, not all food SMEs have a boiler. EW can perform effectively even at temperatures lower than 50ºC. The portable electrolysis sanitation unit with "all in one" functionality may solve several limitations in food SMEs.

In designing a portable electrolysis sanitation unit, an electrolysis system needs to be investigated thoroughly. However, reports on the design of electrolysis systems mainly were patented. The detailed information about its mechanism, and the effects of electrolysis efficiencies and different electrolyzing parameters (e.g., types of electrodes, electrolysis time, salt concentration, and electrical voltage), is very limited. Therefore, the purpose of this study is to investigate information on the effects of different electrolyzing parameters on EW's chemical and physical properties, which will be useful in designing an electrolysis system and choosing operation conditions.

Moreover, the proposed green sanitation program in this research can be used as a guideline to design a sanitation program for other food industries. Food manufacturers should perform preliminary sanitation testing using different sanitation parameters to determine their factory's final and optimal sanitation program. This optimal, economical, and green sanitation program can help achieve excellent sanitation, save sanitation costs, and reduce less harmful substances toward the environment.

1.3 Research hypotheses

Based on the literature review, previous experience, and preliminary studies, the hypothesis of the study is developed as follow:

I. From the literature review, sanitation (cleaning and disinfection) parameters are essential for achieving efficient sanitation. However, previous works mainly were conducted at the laboratory without considering industry operation factors. In this work, the investigation was done at industry premises. This has led to a better understanding of industry issues in achieving efficient sanitation.

II. Previous works have reported that electrolyzed water (EW) works excellently as a green sanitation solution for sanitation of dirty and contaminated food-contact surfaces. However, there is no paper that reported on the ability of EW to remove fat-based residues. In this work, EW was used as a sanitation solution for the sanitation of stainless steel plates inoculated with fat-based residue. This will lead to a replacement of EW for commercial sanitation solutions in frozen meat patty factories, in which fat-based residue is a major sanitation issue.

III. From the literature review, the ion exchange that occurs during electrolysis leads to changes of physicochemical properties (pH, oxidation-reduction potential (ORP), free chlorine, total chlorine, dissolved oxygen, electrical conductivity) of EWs (AcEW and AlEW, in anode and cathode chambers, respectively). Ion exchange depends on the electrolyzing parameters (electrode type, NaCl concentration, electric voltage, and electrolysis time). However, different EW generators might have different limits. The generator's limit implies the operational limit (voltage, electrolysis time, salt concentration) of the generator, at which the generator can produce desired EW properties with less corrosion at the electrodes. In this work, the optimization of the electrolyzing parameters (electrode type, NaCl concentration, electric voltage, and electrolysis time) on the production of EW with effective physicochemical properties was conducted. The result from the optimization can ensure that the EW generator could be used for a long extended period and that the economic usage conditions were achieved.

IV. Several papers reported that both EWs (acidic electrolyzed water (AcEW) and alkaline electrolyzed water (AlEW)) are bactericidal due to their physicochemical properties (pH, oxidation-reduction potential (ORP), free chlorine, total chlorine, dissolved oxygen, electrical conductivity). *Escherichia coli* is a prominent foodborne pathogen related to food processing, particularly processed meat. There is no report on the bactericidal of EWs against *Escherichia coli* ATCC 10536. *Escherichia coli* ATCC 10536 are isolated from meat. Most researchers used *Escherichia coli* O157:H7. Thus, in this work, sanitation experiments were conducted to check the ability of the EW generated at optimized parameters to deactivate the prominent foodborne pathogen (*Escherichia coli* ATCC 10536). The result will lead to the replacement of commercial disinfectants in frozen meat patty factories.

V. From the literature review, the high pH, low ORP, and the presence of NaOH components contribute to the ability of AIEW as a cleaner. Based on the author's reading, the ability of AIEW as a cleaner or degreaser to remove the fat-based residues has not been reported elsewhere. In this work, the effectiveness of the AIEW for sanitation of the stainless steel surface with or without the presence of fat-based residues was investigated. This will lead to the replacement of commercial cleaners in frozen meat patty factories.

VI. In all countries, a sanitation program is mandatory in the food industry to ensure food safety throughout production processes as prescribed by their food law. However, Food SMEs are facing difficulties in implementing a good sanitation program due to budget restrictions, limited production area, and lack of knowledge on the latest and effective sanitation technology (either cleaning tools or sanitation solutions). In this work, a green sanitation program was designed based on the industry issue of frozen meat patty factories and the replacement of the commercial sanitation solution with electrolyzed water. This green technology will improve sanitation's efficacy and reduce sanitation costs.

VII. A good selection of cleaning tools is necessary for an effective sanitation program. Literature reported that fat-based residue can only be removed using hot water and high water pressure. Moreover, a suitable sanitation solution is also needed to increase sanitation efficiency. Therefore. in this work, the TRIZ method was used to design a conceptual design of a portable electrolysis sanitation unit. TRIZ method is a method used to develop creative solutions to the problem that lies in its removal of contradiction. The improving and worsening feature will be determined based on the findings from data from the industry and laboratory work. This portable electrolysis sanitation unit can generate sanitation solutions (water, AIEW, and AcEW) at different temperatures, water jet pressure, and concentrations. The addition of this cleaning tool is required to complete the green sanitation program. This unit will aid the frozen meat patty industry by lowering sanitation expenses and tackling several sanitation challenges.

1.4 Research objectives

The study begins with an evaluation study of the current sanitation program at a local SME factory (Factory X). A green sanitation program is proposed to replace the current sanitation program. Several factors are considered in designing a green sanitation program which includes: 1) cleaning tools, 2) sanitation parameters (time, temperature, and water jet pressure), and 3) sanitation solutions. Fat-based residue is a major problem in Factory X. EW is a green sanitation solution consisting of AcEW and AlEW that can be used as a cleaning and disinfectant solution. To the best of the author's knowledge, no other researchers have investigated the sanitation of fat-based residue that is inoculated with foodborne pathogens (e.g., *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes*). This work also focuses on developing the conceptual design of a portable electrolysis sanitation unit that will be used as a cleaning tool in the green sanitation program. A systematic methodology for innovation named the theory of inventive problem solving (TRIZ) is applied to getting creative conceptual design ideas by solving the design contradiction. The design contradictions are identified from the findings from the industrial-based and laboratory-based studies.

The objectives of this study are:

1. To evaluate the current sanitation program at a local SME factory (Factory X) that produces frozen meat patty.
2. To optimize the electrolyzing parameters (electrode type, NaCl concentration, electric voltage, and electrolysis time) on chemical and physical properties (pH, oxidation-reduction potential (ORP), free chlorine, total chlorine, dissolved oxygen, electrical conductivity) of electrolyzed water (alkaline and acidic electrolyzed water).
3. To investigate the effect of optimized electrolyzing parameters on electrolyzed water to reduce foodborne pathogen (*Escherichia coli*).
4. To evaluate the effect of electrolyzed water on the sanitation of stainless steel surface inoculated with fat-based residue.
5. To develop a conceptual design of a portable electrolysis sanitation unit that can generate sanitation solutions (water, AlEW, and AcEW) at different temperatures, water jet pressure, and concentrations.

1.5 Significance of the study

This work develops a green sanitation program for SME frozen meat patty factories. This study takes a holistic approach to design a green sanitation program that considers the working environment of the identified SME frozen meat patty factory, the efficacy of sanitation solutions, the influence of food residues, and relevant foodborne pathogen.

Before evaluating real issues in SME frozen meat patty factories, a model factory was chosen. Accurate sanitation data based on the model factory's working environment was evaluated. This evaluation gave a complete understanding of the fundamental issues in the industry. The problem statement of this research was decided based on this industrial-based study instead of just referring to the published literature reviews. From an understanding of the real issues or problems in the SME frozen meat patty factories, a practical sanitation program for the industry can be proposed. There was no standard sanitation program in the food industry. Generally, a sanitation program was designed based on manufacturing type, capacity, and technology. By proposing a sanitation program integrating cleaning tools (industrial cleaning brushes and portable cleaning unit), the identified factory improves significantly in terms of sanitation or hygienic conditions and downtime. However, issues on sanitation solutions still exist.

Therefore, Electrolyzed water (EW), which can be an alternative cleaner and disinfectant is proposed in this research. EW has shown significant sanitation potential for different types of food processing surfaces. EW has also been used as a disinfectant for washing fruits, vegetables, and poultry carcasses. However, no literature published EW's efficacy on the food-contact surfaces with fat-based residues. Different EW generators employ different electrolyzing parameters to produce EW with the same physical and chemical properties. Screening experiments helped reduce the parameter variations in these experiments and provided reliable data on EW properties. The electrolyzing parameter screening methods used a laboratory-scale EW generator. The design of the laboratory-scale EW generator is based on custom-made EW generators that were used in previous research that was conducted in a laboratory. These screening methods were essential to determining the range of electrolyzing parameters for the optimization experiments and ascertaining the generator's limit. The subsequent optimization experiments aimed to ensure the generator could be used for an extended period and that economic usage conditions were achieved.

Then, the evaluation of the efficacy of generated EW at optimized parameters could prove the ability of EW as a disinfectant solution against the crucial foodborne pathogens in the meat industry. Moreover, the sanitation experiments of the stainless steel plate that fouled with and without food matrix (fat-based residues) could confirm EW's ability as an effective sanitation solution.

Findings have shown that an additional cleaning tool called a portable electrolysis sanitation unit is significant in completing the green sanitation program. An engineering design tool called the theory of inventive problem solving (TRIZ) method was applied in the development of the unit. The TRIZ method engaged the process of improving features and eliminating its subsequent worsening feature simultaneously through its purpose systematic and guided approach. The features or parameters (either improving or worsening) were based on the experience and data determined from the industry and the laboratory-based study. It is expected that the developed conceptual design of the portable electrolysis sanitation unit could increase more benefit to the frozen meat patty industry by reducing sanitation costs and addressing numerous sanitation issues.

1.6 Limitation of the study

There are two approaches in this study, which are industrial-based and laboratory-based studies. Both approaches were targeted to clean food contact surfaces that have fat-based residue. The removal of loose dirt or meat by water does not mean the cleaning is complete. The fat-based residue will still exist and must be removed. The fat-based residue could be colorless and could be detected using touch inspection. The industrial-based study was performed at one identified SME frozen meat patty factory and this factory was used as a model factory. The working environment and sanitation procedure at the model factory and the effect of using a portable cleaning unit were evaluated. The findings have the potential to be adapted to other frozen meat patty industries despite the study only considering the model factory working environment. Then, the laboratory-based studies involved optimization of the electrolyzing parameters for EW production and evaluation of bactericidal activity and cleanability of EW. These works were performed at the laboratory because validation test, which includes microbiology analyses can be costly when conducted at an industrial scale. Moreover, the existing laboratory-scale electrolysis unit can generate EW in a smaller amount, hence not suitable for industry work. The sanitation study at the laboratory stage focuses on the efficacy of EW during the detergent wash and disinfecting rinse steps only. Two types of alternative sanitation solutions were involved: AlEW was investigated as a cleaning solution and AcEW as a disinfection solution. Neutral electrolyzed water (NEW) was not studied in this work. The bactericidal activity evaluation was against *Escherichia coli* ATCC 10536 only. *Escherichia coli* ATCC 10536 was isolated from meat. *Escherichia coli* is the indicator of unhygienic handling and storage of prepared foods. It is one of the prominent foodborne pathogens related to food processing, particularly processed meat. Findings from laboratory-based and industrial-based studies were used to provide design parameters for the portable electrolysis sanitation unit. However, the design work only reaches a conceptual design phase. The unit fabrication is beyond the scope of this work. The fabrication of the portable electrolysis sanitation unit was delayed several times. To counter the COVID-19 pandemic, the Malaysian government implemented the Movement Control Order (MCO) on 18th March 2020, which was extended a few times, and led to the fabrication factory being ordered to close.

1.7 Structure of the thesis

The description of this work is arranged into eight chapters. The following chapters provide specific explanations concerning this research.

Chapter 1 introduces the background of this study. The chapter continues with the problem statement, hypotheses, objectives, significance, and limitations of the research.

Chapter 2 describes sanitation in the food industry, cleanliness targets, and sanitation factors. This chapter also describes previous studies and their findings in related areas of EW and EW generators.

Chapter 3 describes the method and the equipment used for this work. There are four main parts to this work: 1) Industrial-based study: Evaluation of an effective sanitation program for an SME frozen meat patty factory, 2) Laboratory-based study: Optimization of electrolyzing parameters for green sanitation solutions production, 3) Laboratory-based study: Sanitation of stainless steel surfaces using green sanitation solutions (electrolyzed water), and 4) Developing green sanitation technology.

Chapter 4 presents the results and discussion for Part 1 (Evaluation of an effective sanitation program for an SME frozen meat patty factory). The current sanitation program in a frozen meat patty factory (Factory X) was observed and a new sanitation program was proposed. The effect of different sanitation parameters is discussed here. Moreover, the data gained in this chapter are used to decide the variables used in the following parts of the study. The most crucial foodborne pathogen found in Factory X, *Escherichia coli,* is used as a bacterial culture for sanitation study in Chapter 6. The data and analysis are used as a guideline to design a portable electrolysis sanitation unit in Chapter 7.

Chapter 5 discusses Part 2 (Optimization of electrolyzing parameters for green sanitation solutions production) whereby a green sanitation solution called EW was investigated. The sanitation program proposed in Chapter 4 uses commercial cleaning chemicals. Thus, Chapter 5 investigates the EW which can be used as a potential replacement for commercial sanitation solutions. The effect of electrolyzing parameters on the physicochemical properties of EW is investigated. The generated EW at optimized parameters is used in a sanitation study in Chapter 6. The physical and chemical properties of EW generated at optimized parameters are used as a guideline to design a portable electrolysis sanitation unit in Chapter 7.

Chapter 6 presents the performance of the optimum EWs (AcEW and AlEW) on the bactericidal activity of the *Escherichia coli* ATCC 10536. Then, the cleanability of the inoculated fat-based residue stainless steel plates using EW is evaluated.

Chapter 7 presents the conceptual design of the portable electrolysis sanitation unit water jet. A systematic approach for understanding and solving problems and a catalyst for innovation and invention called TRIZ is applied. The worsening and improving features were determined based on the findings from industrial-based (Chapter 4) and laboratory-based (Chapters 5 and 6) studies. The TRIZ contradiction matrix was built to determine the appropriate solution for resolving all the design intent problems. This unit was used in the proposed green sanitation program.

Chapter 8 concludes the study and presents some suggestions for future studies on sanitation in food SMEs.

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