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RUHR-UNIVERSITÄT BOCHUM

MechEng
Mechanical Engineering



DESIGN A DESALINATION SYSTEM USING CAPACITIVE DEIONIZATION TECHNOLOGY COUPLING WITH ULTRAFILTRATION TECHNOLOGY

BINH DUONG 2024

Vietnamese-German University

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Ruhr – Universität Bochum
Vietnamese – German University

**Brackish Water Desalination System: Investigating the
Use of Ultrafiltration and Capacitive Deionization with
Integrated Monitoring, Addressing Vietnamese Saline
Intrusion**

Thesis for degree of
BACHELOR OF ENGINEERING

By

PHAM QUANG LINH – ID: 13438



Vietnamese-German University

Supervisor: Assoc. Prof.. Tran Le Luu

Binh Duong, June 2024

Affirmation

I hereby declare that this report (including diagrams, drawings and sketches, etc...) is a product of my own work, unless otherwise referenced. All opinions, results, conclusions, and recommendations are of my own and may not represent the opinions and policies of the Vietnamese-German University.

Pham Quang Linh

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Abstract

The discussion surrounding the extraction of fresh and potable water from saline sources has gathered significant attention from both the academic and industrial sectors. It is widely acknowledged that a mere 1 percent of the Earth's water reservoirs are considered suitable for human consumption, while the remaining portion is either saline or frozen in polar regions. Furthermore, the significant shifts in climate patterns and the rapid expansion of urban areas have notably exacerbated the challenges related to ensuring a sufficient supply of fresh water to meet human needs. In light of these challenges, there is a rising initiative to delve into groundbreaking technologies in the domain of desalination systems in order to alleviate the common obstacles experienced in desalination processes. The main objective of these initiatives is to cement desalination as a more economically advantageous and energy-efficient solution in contrast to traditional technologies that have been utilized over an extended period of time.

Additionally, the influx of saline water into the Mekong Delta area presents a grave risk to the freshwater stocks of Vietnam. Unprecedented levels of saline water intrusion have been observed along the primary rivers in the Mekong Delta, prompting the necessity for immediate action. The proposed endeavor is focused on examining the efficiency of merging Capacitive Deionization (CDI) technology with Ultrafiltration (UF) technology, alongside recent advancements in water treatment techniques. The primary objective is to create a comprehensive system capable of treating saline water from various sources, specifically tailored to address the unique water characteristics present in Vietnam. The project will feature a user-friendly interface system equipped with water quality monitoring sensors to facilitate seamless monitoring and optimization of operational parameters.

The design of both the UF membrane module and CDI unit was specifically tailored to suit the distinct water composition found in Vietnam. To proactively address potential challenges arising from saline intrusion, pre-treatment and post-treatment strategies were integrated into the system. A methodical arrangement of water quality sensors, integrating conductivity, pH, turbidity, and temperature sensors, allows for real-time monitoring of inlet and outlet water quality parameters. These data points are then showcased on a 20 by 4 Liquid Crystal Display (LCD) screen to streamline the monitoring process for operators, consequently enhancing the practicality of the project.

The assessment of the system's performance was predicated on factors like permeate water quality (salinity reduction) and operational efficiency (energy consumption and permeate yield). The significance of water quality monitoring in optimizing system operations and ensuring water quality was thoroughly scrutinized. This analysis underscores the feasibility and effectiveness of the UF-CDI system in treating brackish water in Vietnam that is impacted by saline intrusion. The integration of water quality monitoring emerges as a crucial element in enhancing system performance and safeguarding water quality. Subsequent research endeavors could focus on upscaling the system and further enhancing desalination efficiency.

The pilot scale desalination system demonstrated its capability of reducing the concentration of contaminants from over 200ppm in a 550ppm feed water, achieving a remarkable decrease to approximately 350ppm. This achievement is particularly noteworthy given the fact that this system operates with minimal consumption of electrical energy in comparison to alternative desalination technologies like Reverse Osmosis (RO). Moreover, it is imperative to highlight the crucial role played by pretreatment technologies such as microfiltration (MF) and ultrafiltration (UF) in enhancing the overall performance of desalination processes. These preliminary treatment steps significantly contribute to improving the efficiency and effectiveness of the desalination system as a whole.

Keywords: Capacitive Deionization, Ultrafiltration, Automation, Activated Carbon, Brackish water treatment, Optimization for Desalination system, Micro-controller.

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1. Introduction

1.1 Global freshwater scarcity and increasing demand

Freshwater, a vital commodity for each nation globally, is progressively diminishing, even though water bodies account for seventy percent of the Earth's surface. The significance of freshwater in sustaining human activities and life is immense, particularly considering that only a minute fraction, approximately one percent, of the abundant water sources is freshwater; however, its distribution is uneven, plagued by pollution, and subject to unsustainable management practices [1]. The remaining water exists predominantly in the form of ice in polar regions and in the oceans, posing challenges in accessing these vast water reservoirs for human utilization. Recent discoveries from UNESCO, as of 2023, uncover a stark reality where almost half of the world's population struggles with water scarcity problems for at least a month each year, thereby presenting a serious danger to various aspects of people's livelihoods, such as food security and electricity accessibility []. Besides, a remarkable number of 2 billion individuals, constituting 26 percent of the global population, lack access to safe drinking water, while 3.6 billion people, representing 46 percent of the populace, face substandard sanitation conditions []. Projections from the report also indicate a troubling forecast, estimating that the number of urban dwellers worldwide facing water scarcity challenges could escalate twofold, surging from 930 million individuals in 2016 to a staggering 1.7-2.4 billion people by 2050 [].

Figure 1 provides a clear illustration that agriculture stands out as the primary consumer of freshwater, amounting to 70 percent of the overall accessible freshwater on a global scale; however, it is worth noting that a significant portion of this valuable resource, specifically 60 percent, is unfortunately lost as a result of inefficiencies in irrigation systems, characterized by leakages (Panhwar, A., Abro, R., Kandhro, A., Rauf Khaskheli, A., Jalbani, N., Ali Gishkori, K., ... Qaisar, S., 2024) []. In the year 2007, an interview was conducted by the Food and Agriculture Organization with General Dr. Jacques Diouf, during which he expressed that a minimum of 200 liters of freshwater is required per day for an individual to fulfil fundamental requirements such as drinking, cooking, and sanitation, as indicated in figure 2 []. This underscores the critical importance of access to an adequate supply of freshwater for meeting essential human needs.

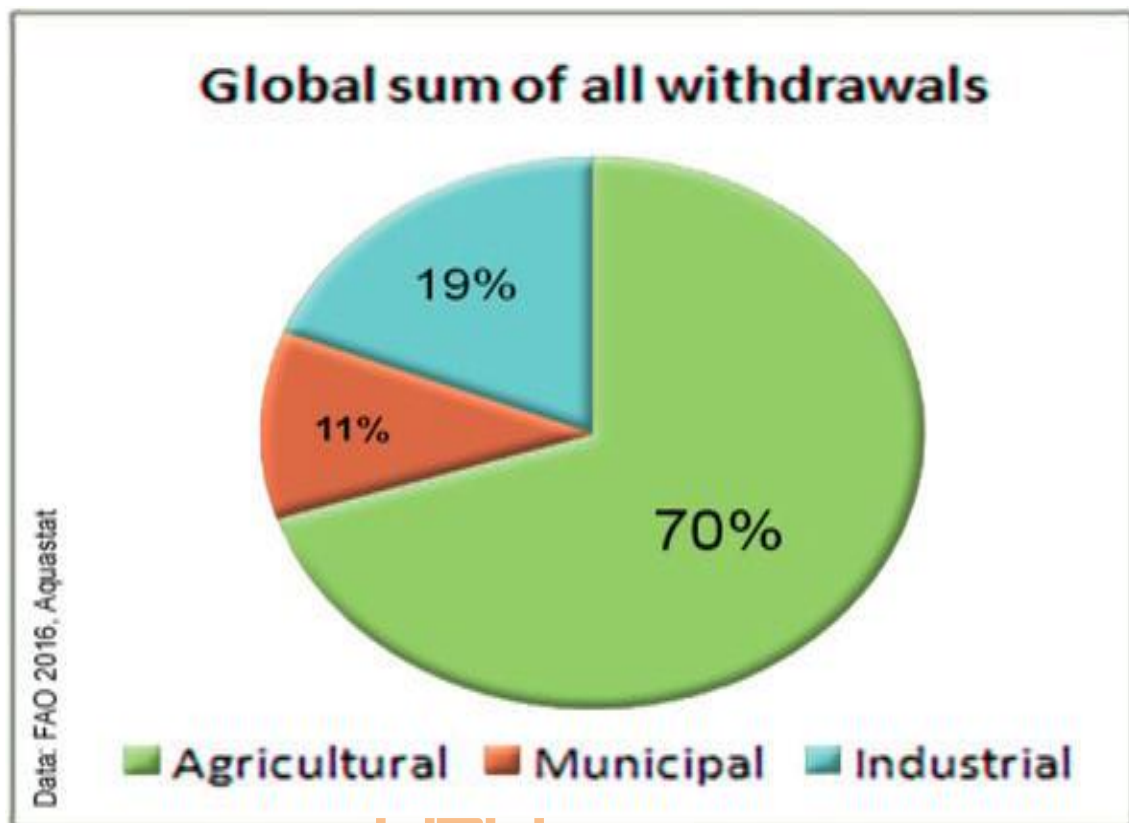


Figure 1: Basic water requirements (for one person) for human needs [].

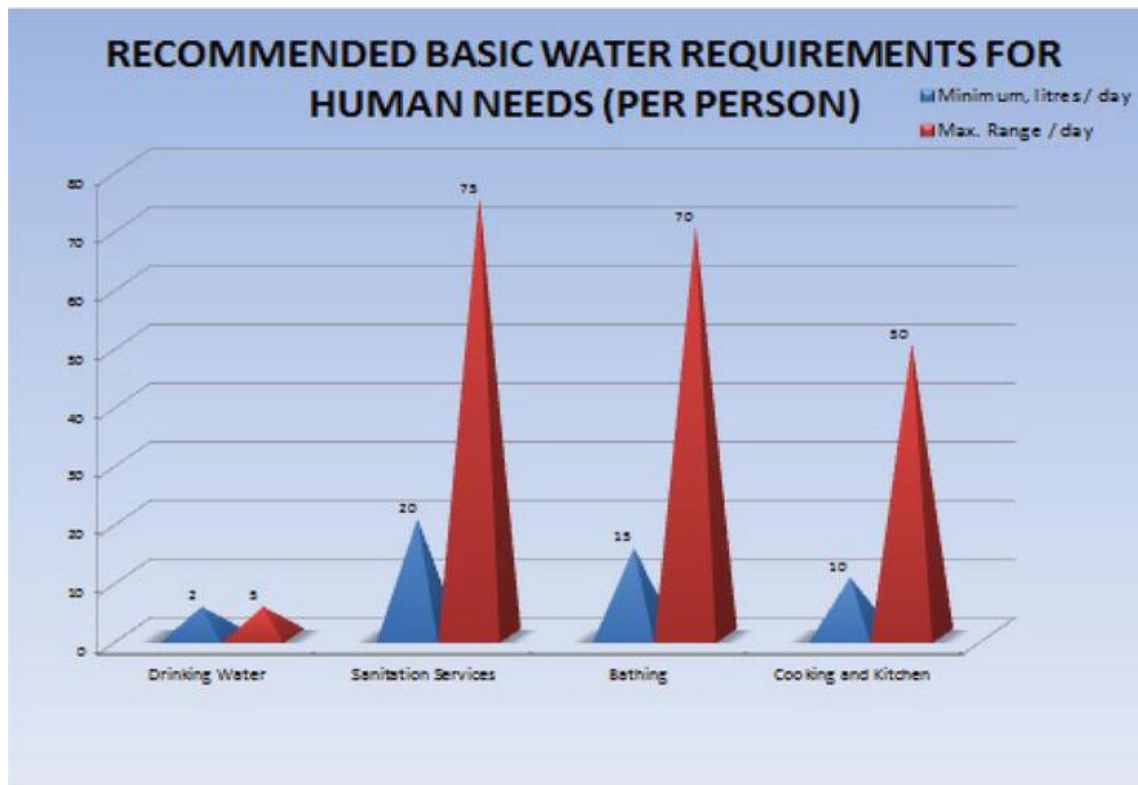


Figure 2: Global sum of water needed for human [].

The problem of water scarcity emerges in two distinct ways: physical water scarcity, arising from a natural lack of water availability, and economic water scarcity, fueled by economic, social, and political elements that hinder the fair distribution of freshwater resources. Additionally, the shortage dilemma is worsened by a variety of factors, such as a growing global population, the persistent effects of climate change, increasing pollution levels, and a continuously rising demand for freshwater resources. Recent assessments dating back to 2011 underscore the severity of the situation, revealing that more than half of the world's river basins were grappling with acute water shortages, directly impacting the local ecosystems in adverse ways and exacerbating the already precarious environmental flow requirements as highlighted by Arjen, Ysbert, Hoekstra, and Mesfin, Mekonnen in their study conducted in 2011.

Table 1: Distribution of water (in percentage) in various sources on Earth [].

Water distribution	Percentage (%)
Ocean water	97.2
Glaciers and other water under ice forms	2.15

Groundwater	0.61
Freshwater lakes	0.009
Inland seas	0.008
Soil moisture	0.005
Atmosphere	0.001
Rivers	0.0001
Percentage earth's surface covered by water	71
The molecules of water are frequently situated at a considerable distance from the Earth's surface, rendering extraction economically infeasible, or they may be exposed to high levels of contamination.	2.5
Availability of freshwater on surface of earth.	0.5
Available water on the planet (Cubic Miles)	326 million

1.2. Vietnamese context: Mekong Delta and saline intrusion threat: Impact on agriculture, water supply, and ecosystems

The region known as the Mekong Delta, distinguished for being the most fertile area supporting Vietnamese agriculture and serving as a pivotal hub of economic activities, is currently facing a growing threat stemming from the encroachment of saline water penetrating deep into the core of its territory. This intrusion of saline water brings about a severe and devastating impact on the largest delta in Vietnam, a nation heavily dependent on agricultural exports as a cornerstone of its economic well-being. The amplification of climate change-related occurrences plays a significant role in the continuous elevation of sea levels, further intensifying the already delicate ecological balance of the Delta. This situation is predicted to bring about profound consequences, affecting agricultural productivity, the availability of freshwater for human consumption, and the general health of coastal ecosystems. Given the complex nature of this urgent matter, there is a critical requirement for the creation and application of novel approaches directed towards safeguarding freshwater reservoirs and guaranteeing the enduring sustainability of the Mekong Delta. These initiatives are indispensable in addressing the detrimental impacts of saline encroachment and in guaranteeing the future viability of the local agricultural, environmental, and socioeconomic frameworks.

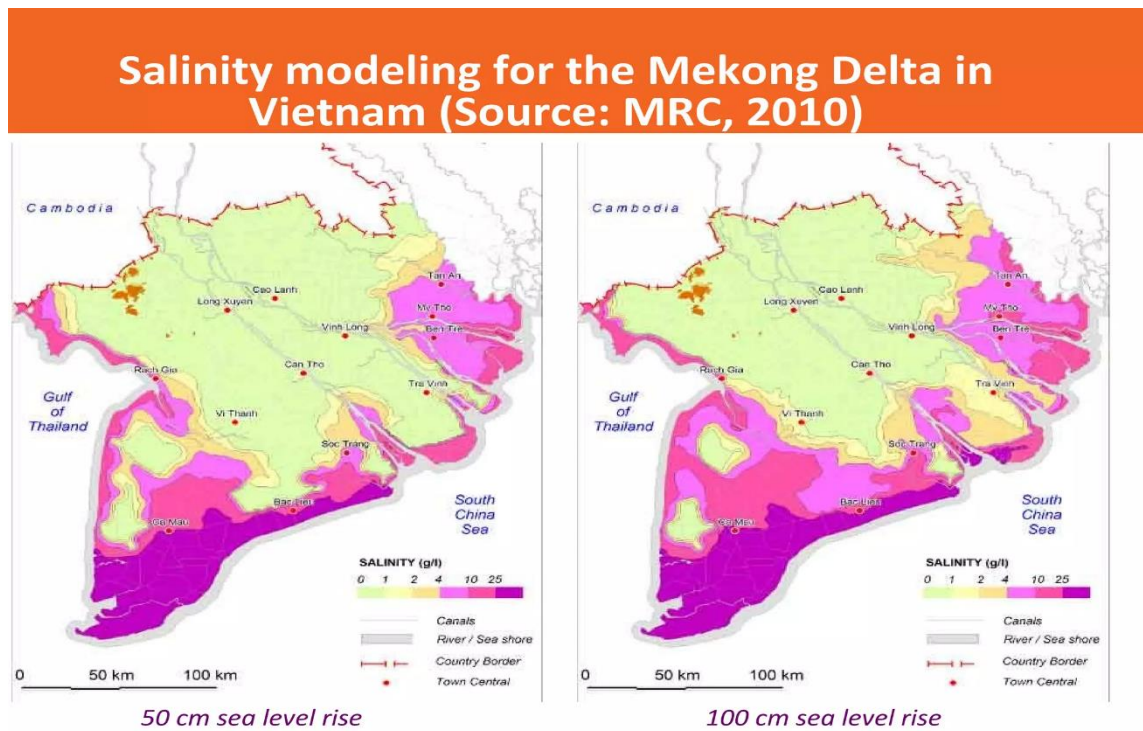


Figure 3: Salinity map, modelled for the Mekong Delta in Vietnam, with 50 cm and 100 cm sea level rise (elwyngj, 2013) [1].


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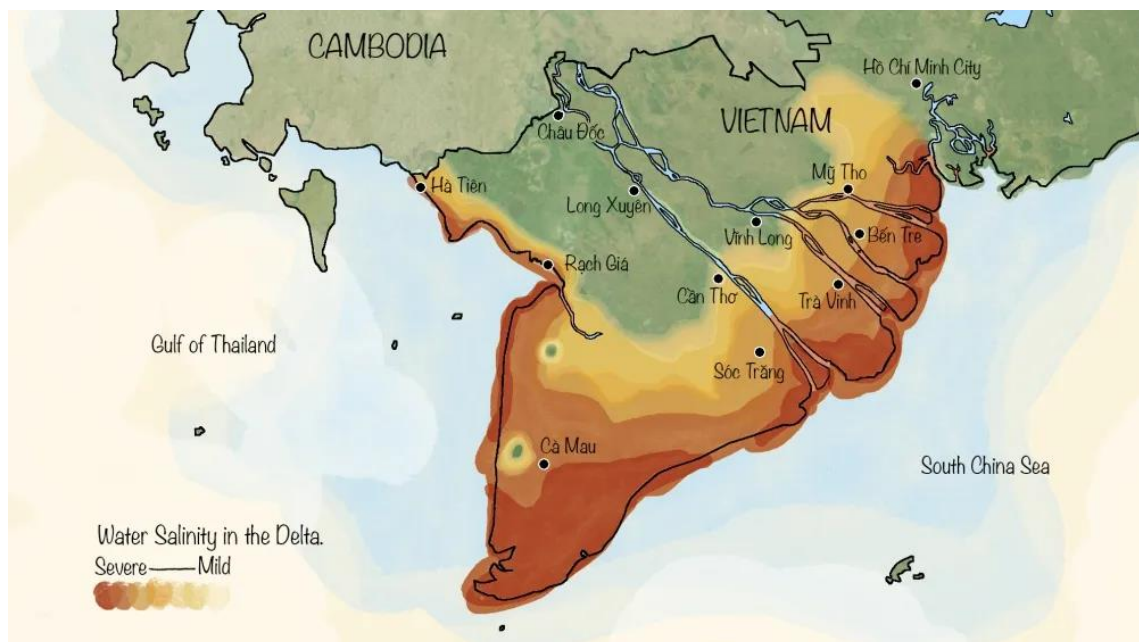


Figure 4: Continuation of saline intrusion into the Mekong Delta in 2019 (Zoe Osborne, 2020) [2].

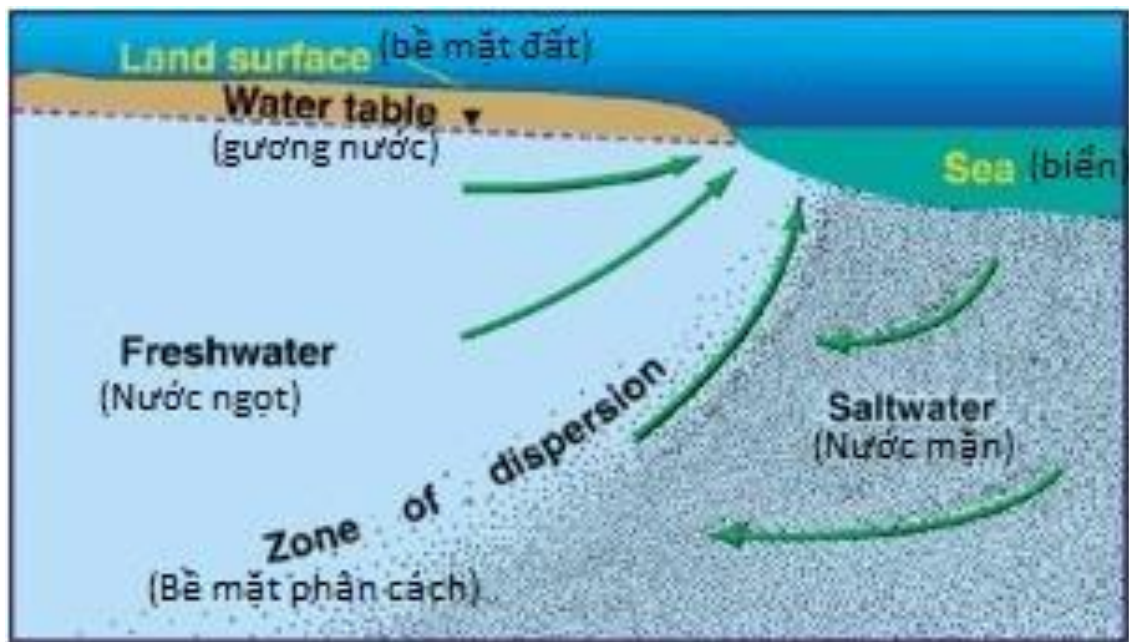


Figure 5: How salted water invasion affects surface and ground freshwater (EOE, 2012) [1].



The invasion of saltwater has a notable effect on the crop productivity in the Mekong Delta and various other agricultural regions, as it disturbs the cellular and physiological functions of plants, resulting in decreased yields and imperilled sources of income for farmers. The condition in the Mekong Delta is further complicated by the impact of climate change, which has heightened salinization and caused extensive damage to crop like rice, vegetables, fruit trees, and seafood, forcing farmers to explore alternative agricultural practices such as shrimp farming, which possess the capacity to endure brackish water conditions. This shift in farming methods demonstrates the adaptation strategies being employed in response to the challenges posed by saltwater intrusion and highlights the complex interactions between environmental factors and agricultural practices in vulnerable regions like the Mekong Delta (Thu, Thi, Bich, Ngo., Hong, Quan, Nguyen., Timothy, Gorman., Quang, Ngo, Xuan., Phuong, Thi, Ngo., Ann, Vanreusel., 2022). The underground infiltration of saline water results in an increase of the levels of soluble salts within the soil, causing a disturbance in the equilibrium of osmosis between the roots of plants and the surrounding soil, leading to the hindrance of nutrient intake and water absorption by the plants, consequently impacting the growth and productivity of the plants in the long run as highlighted by Robert, Akam., Guillaume,

Gruere., in 2018 []. Furthermore, the salinity levels observed in the river water within the Mekong Delta region have surpassed the thresholds that the most robust rice species can withstand, emphasizing the critical necessity for the development and implementation of water treatment and desalination methodologies to alleviate the negative consequences of salinization (Priyanka, Srivastava., Qiang-Sheng, Wu., Bhoopander, Giri., 2019) [].

1.3. Advantages of UF-CDI technology for brackish water desalination

1.3.1. Brackish water definition and potential for desalination

Brackish water, defined as water with a salinity range between freshwater and seawater, is a valuable resource for desalination due to its lower salt content compared to seawater []. However, the presence of various contaminants, such as suspended solids, organic matter, and microorganisms, can pose challenges for efficient desalination processes []. Therefore, appropriate pretreatment technologies are crucial to enhance the overall performance and efficiency of desalination systems.

This type of brackish water environment is often a result of the mixing of sea water and freshwater and contains a large amount of both anions and cations such as Na⁺, Cl⁻, SO₄²⁻, and Mg²⁺ (Hendrik, Schubert., Dirk, Schories., Bernd, Schneider., Uwe, Selig, 2017) []. These anions and cations contribute significantly to the level of salinity; therefore, main desalinating processes should focus on extracting these four main ions to reduce salt in brackish water.

Furthermore, irrigation with highly salted water for crops can affect the growth of a plant as well as reduce grain yield, and cadmium uptake in maize (Yuzhao, Ma., H., Dang., Ke-Jiang, Li., Chunlian, Zheng., Caiyun, Cao., Junpeng, Zhang., Quanqi, Li, 2022) []. Thus, pushing for new and novel desalinating systems to supply water that is much needed for agricultural, industrial, and human purposes.

1.3.2. Advantages of combined desalinating system

Ultrafiltration (UF) has garnered significant attention in recent years as an emerging technological advancement poised to bring about enhancements in water treatment procedures by effectively eliminating various contaminants such as toxic ions,

heavy metals, proteins, and microplastics originating from a wide spectrum of water sources, including but not limited to dairy industrial wastewater and industrial wastewater. The UF technology operates by employing membranes equipped with designated pore sizes aimed at substantially diminishing undesired species during the treatment processes as discussed by Mohammad, Y., Ashfaq., Mohammad, A., Al-Ghouti, 2023.

Capacitive deionization (CDI) has emerged as a novel and validated technology showcasing potential as an effective method for desalinating brackish water by leveraging porous carbon-based electrodes to extract charged ions and molecules from water through the application of minimal voltage levels, sometimes as low as 1.2 volts, as explicated by Kamran, Salari., Payam, Zarafshan., Morteza, Khashehchi., Gholamreza, Chegini., Hamed, Etezadi., Hamed, Karami., Joanna, Szulżyk-Cieplak., Grzegorz, Łagód, 2022. This approach is garnering growing interest from academic and industrial circles, emerging as a promising technological breakthrough that offers a more energy-efficient and economically feasible alternative to conventional methods like reverse osmosis and distillation. CDI has demonstrated remarkable efficacy in cycles, commendable reversibility, and a diminished energy footprint, positioning it as a highly promising approach for desalination purposes, as evidenced by the research conducted by Ronghao, Wang., Kaiwen, Sun., Yuhao, Zhang., Chen, Qian., Weizhai, Bao, 2022.

The amalgamation of Ultrafiltration (UF) and Capacitive Deionization (CDI) holds the potential to yield numerous advantages in the treatment of brackish water, thereby presenting itself as a promising solution particularly suitable for regions such as Vietnam currently grappling with severe saline intrusion issues. Nevertheless, despite its merits, UF-CDI system encounters certain challenges when transitioning into practical applications, a topic that will be extensively delved into within the context of this thesis.

- Enhanced Salt Removal Efficiency: Ultrafiltration (UF) membranes exhibit a high capability in eliminating larger particles and a significant proportion of dissolved salts. Moreover, Capacitive Deionization (CDI) effectively eliminates dissolved ions via electrostatic attraction, ultimately achieving remarkable desalination efficiency.

- Reduced Energy Consumption in Comparison to RO: In contrast to Reverse Osmosis (RO), a widely renowned desalination method, UF-CDI necessitates lower pressure, consequently leading to decreased energy utilization when treating water with lower salinity levels such as brackish water.

- Scalability and Modular Configuration: The modular designs of UF and CDI units offer scalability, thus proving advantageous for commencing operations with a pilot-scale system and facilitating subsequent expansion.

1.4. Thesis objectives

This project is aimed at accomplishing the objective of developing and building a suitable desalination system specifically designed for household use. The system not only serves as a pilot-scale model but also paves the way for the future implementation of these newly developed techniques in the treatment of brackish water processes. Additionally, this study evaluates the system's performance in relation to different aspects of water quality. These factors encompass various indicators such as pH levels, total dissolved solids (TDS), colour, and water transparency, all of which are vital for assessing the system's efficiency.

The incorporation of a real-time monitoring system is expected to offer numerous benefits in enhancing efficiency and operational parameters. Despite being equipped with a diverse array of sensors and capable of autonomous operation, it is imperative that users can assess the system's status without dismantling it. The addition of a user-friendly interface menu plays a vital role in aiding users to comprehend the system's functioning, which is essential if the project is to achieve its objective of providing convenience.

Several large rivers in Vietnam have been the subject of reports indicating the challenging issue of increasing saline intrusion. The governmental observing stations, along with experts in the field, have issued warnings highlighting the concerning developments. Specifically, it has been documented that there are two significant demarcation lines symbolizing the encroachment of saltwater, with concentrations of 1 gram per liter and 4 grams per liter, which have visibly advanced deeper into these river systems [1]. In addressing the predicament presented by the critical situation in Vietnam, there is a pressing need for the development of a sophisticated system that is adept at the process of desalinating water with low to medium concentrations of salt. Furthermore, this system must exhibit a remarkable capability to operate with minimal electrical energy requirements, ensuring efficiency in the desalination process. Furthermore, it is crucial that the system is designed to be user-friendly, ensuring that individuals with different levels of technical skill can operate it with ease. Moreover, it is vital that the environmental impact of such a system is minimal, achieved through its independence

from the use of chemicals typically required to maintain stable and effective operating conditions. It is noteworthy that the by-products formed by this system are not expected to greatly impact agricultural land, thereby securing sustainability and environmental preservation.

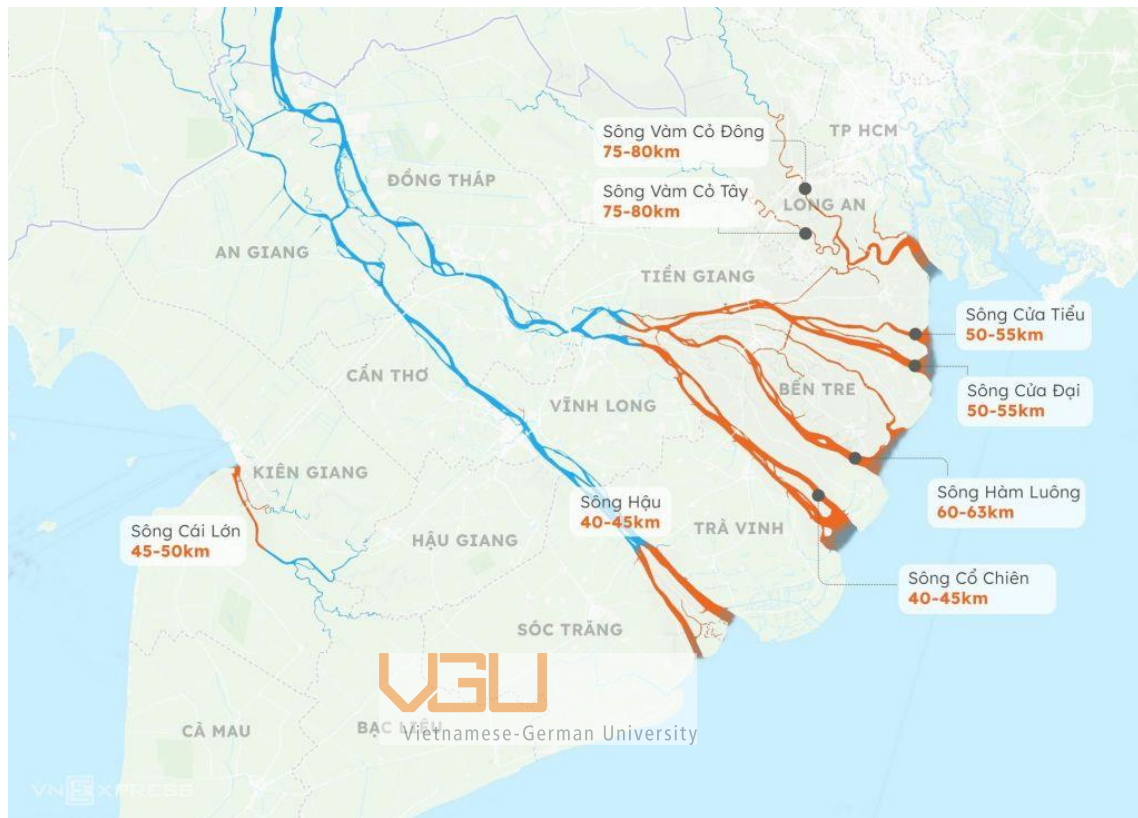


Figure 6: Saline intrusion with concentration of 4g/L recorded on major rivers in Vietnam [1].

II. Literature Review

2.1. Activated Carbon

2.1.1. Activated Carbon's utilization in pre-treatment process

Activated Carbon (AC) is regularly applied as a methodology in the primary phases of water treatment, chiefly owing to its exceptional aptitude to adsorb a wide variety of contaminants. The utilization of this technology has been widely embraced and incorporated in diverse industries and settings globally, due to its effectiveness in eliminating organic micropollutants, natural organic matter (NOM), and other detrimental substances, thereby enhancing overall water quality. For instance, the activated carbon-activated sludge (AC-AS) process has demonstrated significant potential in treating wastewater containing high levels of toxic compounds, leading to improved removal efficiency and reduced treatment durations compared to conventional approaches, as indicated in a study by Guanying, Wang., Guanglei, Qiu., Jianhua, Wei., Zhuangyan, Guo., Weiye, Wang., Xiaoling, Liu., Yonghui, Song., in 2023; thereby underscoring the efficacy of Activated Carbon in water purification processes in figure 7.

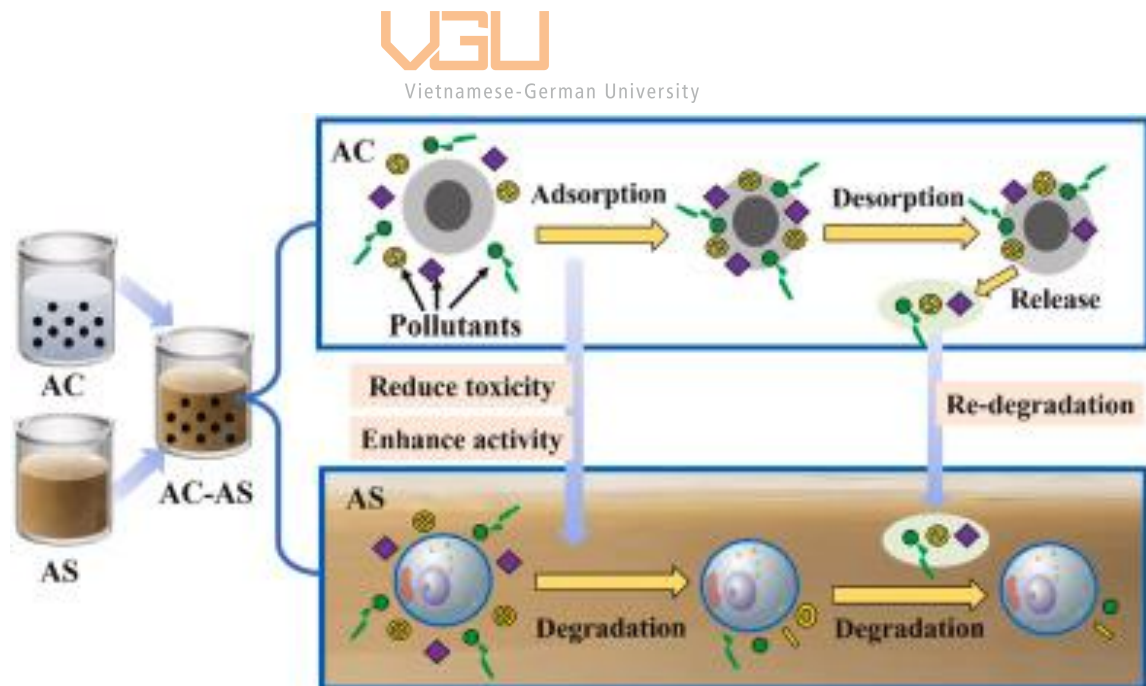


Figure 7: AC-AS mixture's effects on chemical explosion accident wastewater treatment [1].

The significant role played by the material characteristics of activated carbon (AC), specifically the surface oxygen groups, in determining its adsorption efficiency is widely recognized within the realm of scientific investigations. The utilization of advanced analytical techniques like thermogravimetric analysis (TGA) along with Fourier-transform infrared spectroscopy (FTIR) has the potential to provide valuable insights for identifying the most appropriate types of activated carbon to effectively address specific pollutants in a wide range of applications. This approach could enable researchers to gain a deeper understanding of the interactions between activated carbon and various pollutants, thus facilitating the development of tailored solutions to address environmental challenges more efficiently and sustainably (Daniel, Dittmann., Leon, Saal., Frederik, Zietzschmann., Maike, Mai., Korinna, Altmann., Dominik, Al-Sabbagh., Pia, Schumann., Aki, Sebastian, Ruhl., Martin, Jekel., Ulrike, Braun., 2022) []. The effectiveness of Powdered activated carbons (PACs) was demonstrated in the 2022 paper, as it was observed that these PACs were able to remove carbamazepine with an efficiency exceeding 80 percent across all types of PACs when a dosage of 10mg per liter was used; this particular discovery serves to highlight the direct correlation between the adsorption capacity of ACs and the presence of a well-developed pore network and internal surface area, both of which are outcomes resulting from the utilization of various production methods [].

Table 2: Powdered activated carbons that were investigated, and the abbreviation used [].

Name	Manufacturer	Raw material	Activation	Abbreviation
HK 950	Carbon Service & Consulting	Wood charcoal	Phosphoric acid	Wood1
HKP 1050	Carbon Service & Consulting	Wood charcoal	Phosphoric acid	Wood2
CCP 90D	Donau Carbon	Coconut shell	Steam	Coco1
SAE Super	Cabot (Norit)	Mixture, Lot 3868836	Unknown	Mix1
5000 P-f	Jacobi Carbons	Lignite	Unknown	Lig1
AZ 1050	Carbon Service & Consulting	Bituminous coal	Unknown	Bitu1

PS-WP 235	Chemviron	Bituminous coal	Unknown	Bitu2
CC 401	Chemviron	Hard coal (reactivate)	Unknown	Hard1

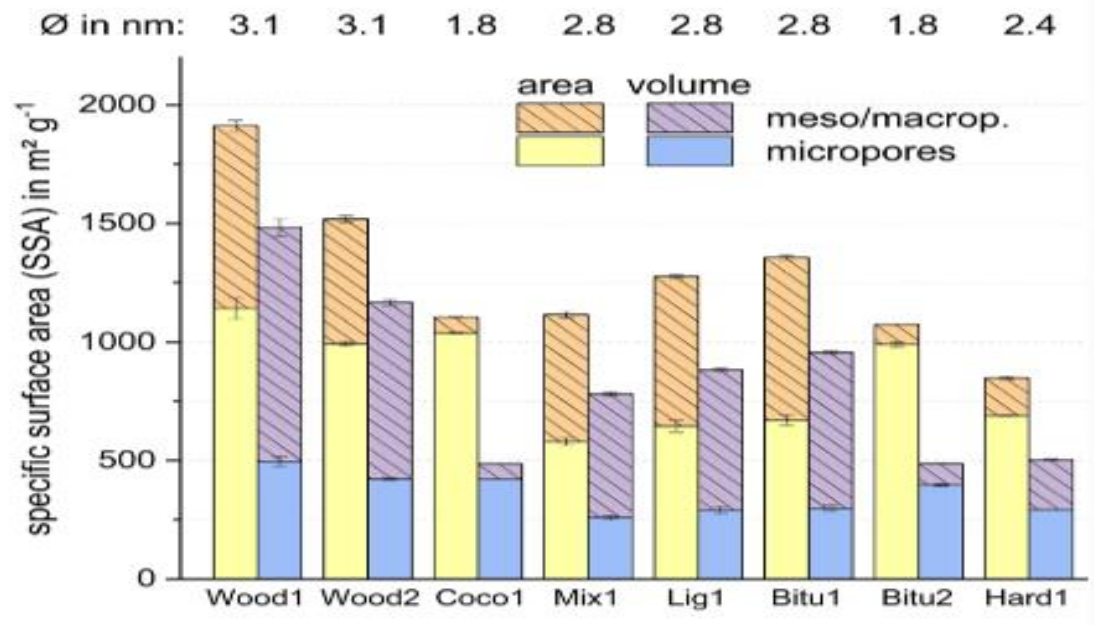


Figure 8: Specific surface area (SSA) and total pore volume of the eight PACs with respective shares of mesopores, macropores, and micropores, with average pore diameters (4 V/A) on top [].

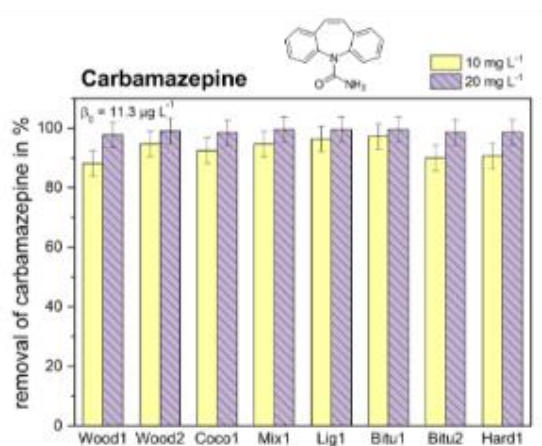


Figure a

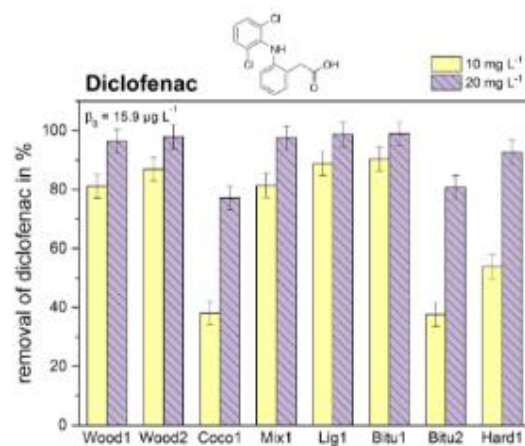
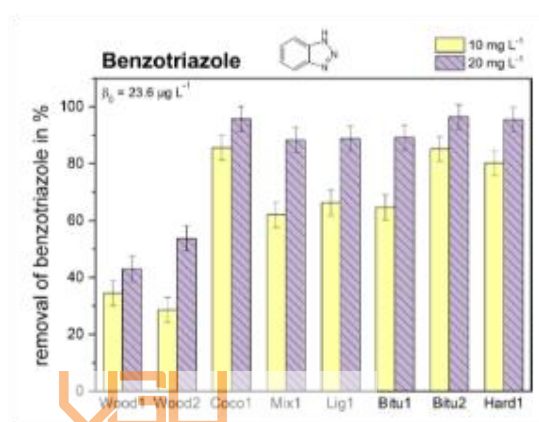


Figure b



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Figure c

Figure 9: Removal capacity of PACs for a) carbamazepine, b) diclofenac, and c) benzotriazole in treated water; at dosage of 10mg per liter and 20mg per liter [1].

The utilization of activated carbon within a range of pre-treatment procedures significantly boosts the effectiveness in eliminating contaminants, thereby presenting itself as a flexible and efficient method for the purification of water sources. This integration enhances the capacity to address a variety of pollutants and contributes to the overall success of water treatment processes.

2.1.2. Sustainable fabrication of electrodes from ACs derived from agricultural byproducts for CDI Technology

Recycling agricultural by-products is indispensable for mitigating environmental pollution and improving the value of products through the efficient utilization of waste materials. This practice not only aids in reducing the negative impact on the environment

but also adds value to the products by incorporating waste materials in a resourceful manner. Hence, opting to produce activated carbon from such waste materials not only represents a sustainable decision but also aligns with established academic research, as these byproducts are typically rich in carbon content, a characteristic that has been consistently observed, such as wood, coconut shells, and other plant materials. ACs derived from this plentiful and easily accessible source further increase resource efficiency and reduce pressure on other non-renewable resources like coal, which are traditionally used to make AC.

Table 3: Activated carbon derived from agriculture by-products [].

Material	Activation agent	Activation time (min)	Activation temperature (°C)	Surface area (m ² /g)	Yield (%)	Volume (m ³ /g)
Coconut shell	Stream	75	900	2079	42.2	1.212
	CO ₂	210	900	2289	37.5	1.299
	Stream	100	900	946.5	n.a	3.42
	CO ₂	2-8	364-616	625.61	n.a	0.42
	KOH/CO ₂	60	500	79.56	n.a	2.49
	NaOH	60	600	876.14	77	28.6 A ⁰
Walnut shells	ZnCl ₂ /N ₂	120	750	1360	n.a	0.68
Mandari shell	H ₃ PO ₄	60	500	1021	n.a	1.572
Chlorella and spirulina	KOH	20	800	5.7	n.a	0.01
Oyster shells	n.a	120	1000	0.8142	87.3	n.a
Acacia wood	KOH	4.5	360 watt	1045.56	27.96	0.54
Oil Palm	LiOH	15	800 watt	1350	n.a	n.a
Brewery	K ₂ CO ₃	20	800	1405	n.a	n.a

Peanut shells	KOH	120	750	1523.2	n.a	0.533
Bamboo	K ₂ CO ₃ /N ₂	20	900	>1565	n.a	n.a
Mango leaves	KOH/N ₂	60	800	683.146	n.a	0.274

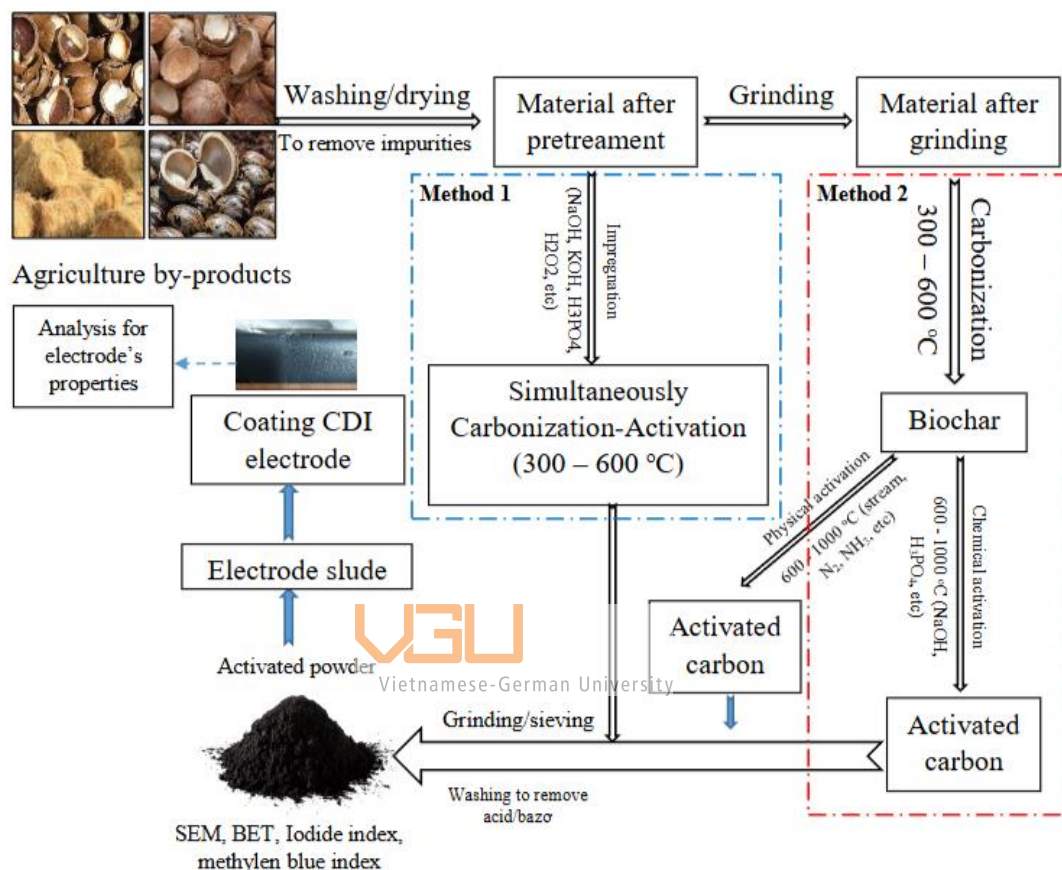


Figure 10: Production of CDI electrodes from activated carbon derived from agricultural waste [1].

The transformation of agricultural waste by-products into activated carbon presents a versatile solution with numerous potential applications, encompassing areas such as water purification, air pollution control, and utilization in the food and pharmaceutical sectors. Such a process not only adds value to the initial by-products but also creates an extra revenue stream for farmers, thereby enhancing their economic prospects. This pioneering approach not only deals with environmental concerns but also stresses the importance of embracing sustainable practices in various industries for long-term gains.

2.2. Membrane filtration technology: Microfiltration and Ultrafiltration

2.2.1. Microfiltration

Microfiltration (MF) technology is a separation process based on membranes, which functions through size exclusion to separate particles and microorganisms from liquid streams. The fundamental operating principles of MF revolve around the utilization of membranes possessing pore sizes typically falling within the range of 0.1 to 10 micrometers. These membranes facilitate the passage of water molecules and small solutes while effectively retaining larger particles and microorganisms within the system (Yaoping, Liu., Han, Xu., Tingyu, Li., Wei, Wang., 2021) []. A study conducted by Shaheen Fatima Anis, Raed Hashaikeh, and Nidal Hilal in 2019 revealed that there has been a growing interest in the technology within the academic community. This interest is clearly evidenced by the upward trend in research activities related to membrane fabrication, wastewater treatment, and fouling studies for microfiltration from the years 2009 to 2018 [].

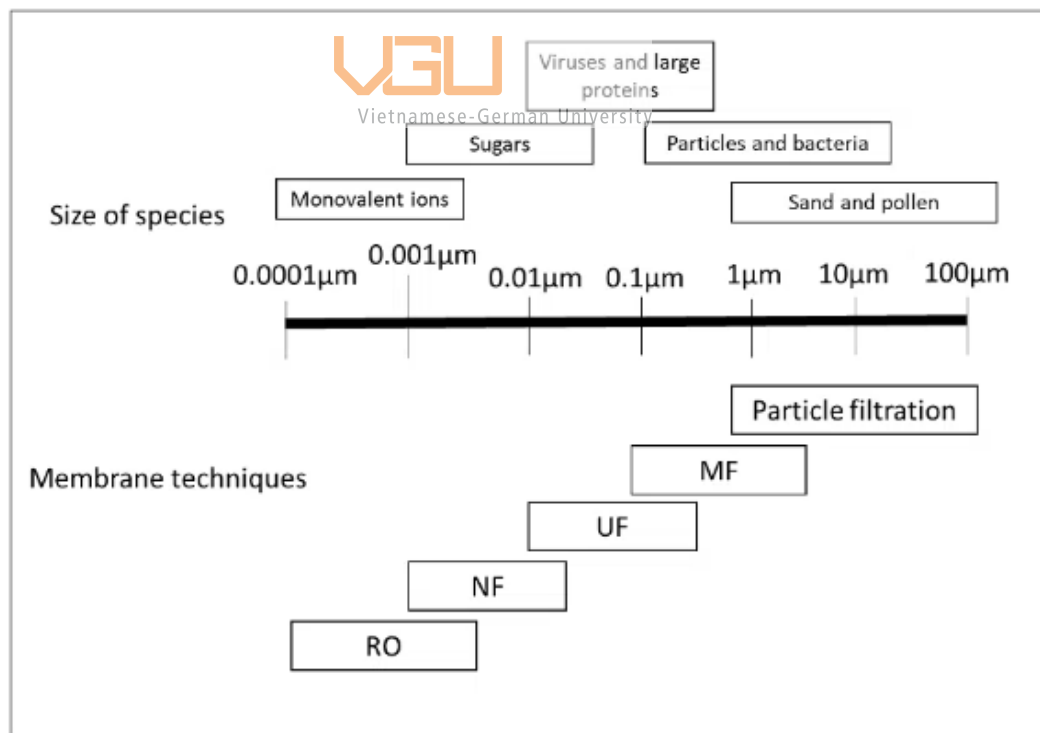


Figure 11: Classification of Microfiltration technology based on pore size and dominant removal species [].

The membrane-based classification of this technology dictates that microfiltration (MF) operates under the influence of a pressure gradient acting across the membrane, thereby

enabling the separation of particles according to their size and deformability characteristics. This filtration process is reliant on the differential pressures established across the membrane to effectively drive the movement of particles and allow for selective permeation based on specific physical properties (Kiana, Aran., Alex, Fok., Lawrence, A., Sasso., Neal, Kamdar., Yulong, Guan., Qi, Sun., Akif, Ündar., Jeffrey, D., Zahn., 2011) []. MF has demonstrated that it can effectively remove a high level suspended solids and organic matter from surface water, which often characterized by a high level of turbidity and total suspended solids (John, Linkhorst., Torsten, Beckmann., Dennis, Go., Alexander, J., C., Kuehne., Matthias, Wessling., Matthias, Wessling., 2016) []. Additionally, MF can be coupled with chemical coagulation to enhance its performance, particularly in removing natural organic matter with removal efficiencies for $\text{NH}_4^+\text{-N}$ and total inorganic nitrogen (TIN), of 96.5 percent and 92.1 percent respectively, as indicated by a study in 2020 by Fei Xiang, Shanshan Sun, Shengbing He, Jungchen Huang, Weili Zhou []. Unfortunately, MF faces significant limitations, primarily due to membrane fouling leading to flux deterioration reached 90 percent in under 1 hour, which can severely impact its long-term performance; making it not suitable for standalone process due to rapid fouling (A., E., Mansi., S.M., El-Marsafy., Yasser, Elhenawy., Mohamed, Bassyouni., 2022) [].

Table 4: Performance of various MF membranes for oilfield produced water treatment [].

Membrane material	Average pore size	Oil concentration (ppm)	Rejection (%)
α -Alumina	2.1 μm	100	55
α -Alumina	0.1 μm	150	61.3
α -Alumina	0.2 μm	26	84.61
NaA zeolite-alumina	1.2 μm	100	98.8
	0.4 μm	100	98.4
Fly-ash-based membrane mixed with quartz and calcium carbonate	1.4 μm	200	99.9

2.2.2. UF membrane technology: overview and membrane selection criteria

Ultrafiltration (UF) technology stands out among various membrane filtration techniques due to its unique applications, notable efficiency in eliminating contaminants, and distinct operational characteristics in water treatment processes. The effectiveness of UF membranes in removing potentially harmful substances from water provides a

significant advantage over other membrane technologies, as they require lower operational pressures. Nonetheless, UF membranes face challenges in achieving optimal decontamination performance for specific elements and are susceptible to fouling-related issues (Mohammad, Y., Ashfaq., Mohammad, A., Al-Ghouti, 2023) []. Contrary to microfiltration (MF), ultrafiltration (UF) has indicated to be a feasible approach for eradicating waterborne viruses and bacteria present in both wastewater and drinking water sources. This successful utilization of UF emphasizes its efficiency in treating aquaculture water, as it can effectively eliminate pathogens without needing elevated temperatures (Vasco, C., Mota., Hanne, Britt, Brenne., Morten, Kojen., Kine, Rivers, Marhaug., M., Jakobsen., 2022) [].

In the realm of drinking water provision, ultrafiltration technology has been experimentally implemented in order to deliver drinking water of superior quality while simultaneously diminishing energy usage and minimizing environmental impact (Federico, León-Zerpa., Jenifer, Vaswani-Reboso., Tomás, Tavares., Alejandro, Ramos-Martín., Carlos, Mendieta-Pino., 2023) []. UF membranes operate at low pressures and have pore sizes ranging from 0.01 to 1 micrometer, making them capable of rejecting microplastics, toxic ions and dyes from wastewater [].

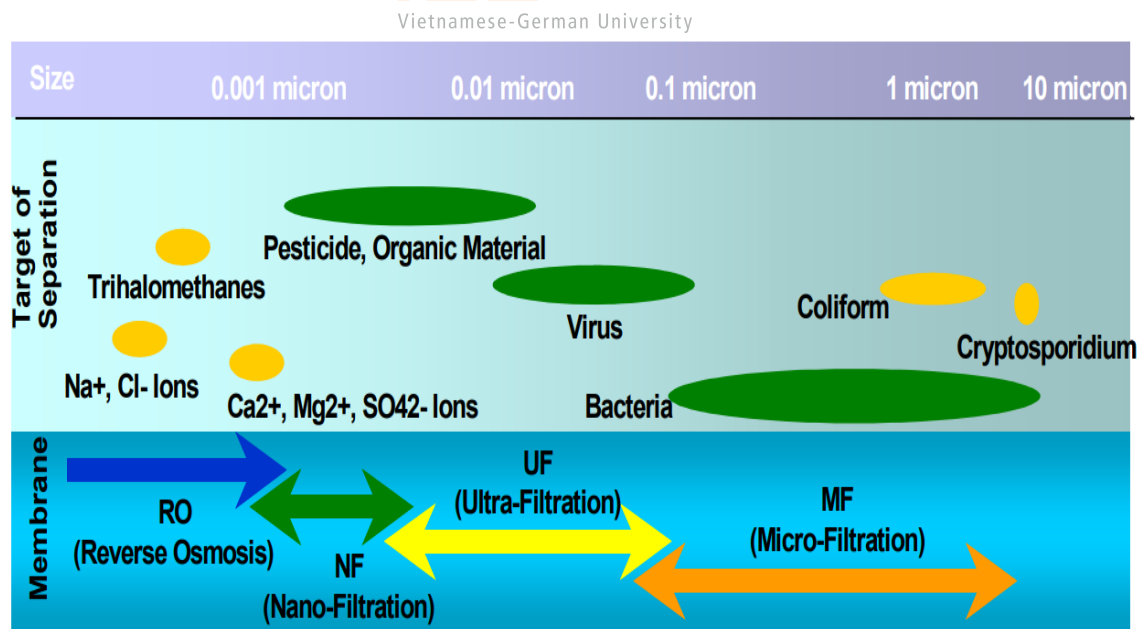


Figure 10: Criteria for membranes process and filtration ranges [].

Table 5: Summary of studies related to the development of UF membranes for heavy metal removal [].

No.	Technique used	Metals studied	Removal efficacy (%)	Adsorption capacity (mg/g)	Remarks
1	Clay-based UF membrane supported on natural zeolite	Chromium	Membrane with six layers Sm/Z6 = 89	n.a	UF composite membranes were obtained via layer-by-layer technique and four different membranes were prepared namely, Sm/Z4, Sm/5, Sm/Z6, Sm/Z7
2	Extracellular polymer substances-enhanced UF (EPS-UF)	Lead Copper Cadmium	94.8 88.9 89.2	n.a	EPS solution formed cake on the UF membrane which was then used to filter contaminated water
3	Polyelectrolyte-enhanced UF followed by dithionite-based chemical reduction	Copper	94	n.a	Polyethyleneimine (PEI) achieved the highest removal at pH 3
4	Internal pore decoration with polydopamine nanoparticles in polymeric UF membrane	Lead Cadmium Copper	92.2 17.01 10.42	20.24 17.01 10.42	Dopamine solution penetrated PES/UF membrane from the reverse direction (PES/PDA-R) and exhibited favorable adsorption performance
5	Polysulfone amine-functionalized nanocomposite membrane	Copper Lead Nickel Cadmium	99.7 98.6 98.4 98.5	n.a	Organic/inorganic 3D nanonetwork was formed by intercalating amino group-functionalized carbon nanotubes and sodium styrene-maleic anhydride copolymer

Initially, the focus of research was on MF and UF for the treatment of surface water, particularly aimed at removing turbidity and suspended solids in place of traditional filtration methods. Over time, attention shifted towards the elimination of microorganisms, specifically targeting cryptosporidium and giardia. Subsequently, there was a shift towards investigating the effectiveness of MF and UF in removing viruses within the size range of 0.02 to 0.08 μm , bacteria sized between 0.5 to 10 μm , and protozoa ranging from 3 to 15 μm . The pore sizes of MF and UF membranes, which

typically fall between 0.01 to 5 μm , function as a physical obstacle. When coupled with various physical and chemical processes, these membranes are capable of filtering out a significant portion of microorganisms based on their respective size distributions. This combination of mechanisms has been found to be particularly effective in the rejection of microorganisms, as indicated by (Lu, Li., Chettiyappan, Visvanathan., 2017) [].

The selection of different pore size is critical, considering the application of UF in different water treatment processes; selection of suitable membranes and module configuration can minimize membrane fouling, which is an inherent phenomenon that cannot be eliminated, conclusion made by Ananya Bardhan, Aanisha Akhtar, Senthilmurugan Subbiah in 2022 [].

2.2.3. Membrane fouling: key factors contributing to membrane fouling in MF and UF technology

Membrane fouling represents a significant challenge in the realm of microfiltration and ultrafiltration technology employed for water treatment purposes. The phenomenon involves the undesired build-up of substances on the membrane's surface and potentially within its pores, thereby causing a decrease in filtration effectiveness. This issue poses a notable threat to the overall operational longevity and environmental sustainability of membrane-centric water treatment facilities. A comprehensive understanding of the fundamental mechanisms and influential factors contributing to membrane fouling is paramount in devising effective mitigation strategies. With this awareness, researchers and engineers can establish and carry out measures targeted at maximizing the performance of microfiltration and ultrafiltration processes. It is essential to delve into the intricacies of membrane fouling to devise targeted solutions that can bolster the efficiency and reliability of water treatment systems reliant on membrane technology [1-3]. In the following discussion, we will delve deeper into the causes, impacts, and potential solutions related to membrane fouling in water treatment application.

1. Li, Q., Elimelech, M. (2015). Organic fouling and chemical cleaning of nanofiltration membranes: Measurements and mechanisms. *Environmental Science & Technology*, 49(1), 15-24.
2. Drioli, E., Ali, A., Macedonio, F. (2015). Membrane distillation: Recent developments and perspectives. *Desalination*, 356, 56-84.
3. Mi, B., Elimelech, M. (2010). Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents. *Journal of Membrane Science*, 348(1-2), 337-345.

The main contributors to membrane fouling were discovered in previous studies and listed below for better understanding of the issue, as indicated by a review paper by Lu Li and Chettiyappan Visvanathan in 2017.

- Natural Organic Matter (NOM) and Colloids: NOM and colloids are the primary contributors to membrane fouling in both UF and MF processes, as they can form a layer on the membrane surface and block the pores, reducing efficiency.
- Hydrophilic and Hydrophobic Compounds: Hydrophilic compounds are major factors contributing to NOM fouling, while hydrophobic membranes are more prone to fouling from organic compounds like alcoholic compounds and polysaccharides due to adsorption.
- Membrane characteristic: The properties of the membrane, such as surface roughness, hydrophilicity, and hydrophobicity, significantly influence fouling. For instance, hydrophilic membranes generally have higher flux and are less prone to fouling compared to hydrophobic ones.
- Pretreatment methods: Pretreatment methods like coagulation and adsorption can help reduce fouling by aggregating fine particles and preventing pore blockage, but they can also sometimes accelerate fouling under certain conditions.
- Operational conditions: Factors like the quality of raw water, chemical dosages, and operational parameters (such as: pressure and flowrate) play vital roles in determining the extent of membrane fouling. Proper management of these conditions can help mitigate fouling issues.

The research findings also highlighted specific protocols essential for upholding the structural integrity of the membrane and ensuring a consistent flow of the water produced. It is strongly recommended to adhere to a routine cleaning regimen for preserving the functionality of the membrane, encompassing procedures such as backwashing and chemical cleaning, which are effective in eradicating accumulated fouling layers and sustaining optimal operational performance. By diligently following these maintenance practices, it is possible to mitigate potential issues associated with membrane fouling and guarantee a smooth and efficient operation of the water production process.

2.3. Capacitive deionization technology: principles, electrode configuration, electrode materials, and important performance metrics.

2.3.1. CDI overview and working principles

Capacitive Deionization (CDI) has gained considerable recognition in the field of scientific exploration as a potential answer for the difficulties connected with water desalination and purification. This innovative and emerging technology employs the fundamental concepts of electrochemical capacitors for the purpose of extracting ions from wastewater. The fundamental operational principles entail the application of an electrical potential across two porous electrodes, commonly composed of carbon-based

materials, that are divided by a separator channel where the brackish water passes through. Upon the activation of the potential, positively and negatively charged ions within the liquid are attracted towards and held in the electrically charged double layers (EDLs) that are established on the surfaces of the electrodes, effectively removing them from the water and thereby reducing its salinity. This method of electrochemical desalination offers a promising solution for addressing water scarcity issues globally by providing a sustainable and efficient approach for producing freshwater resources.

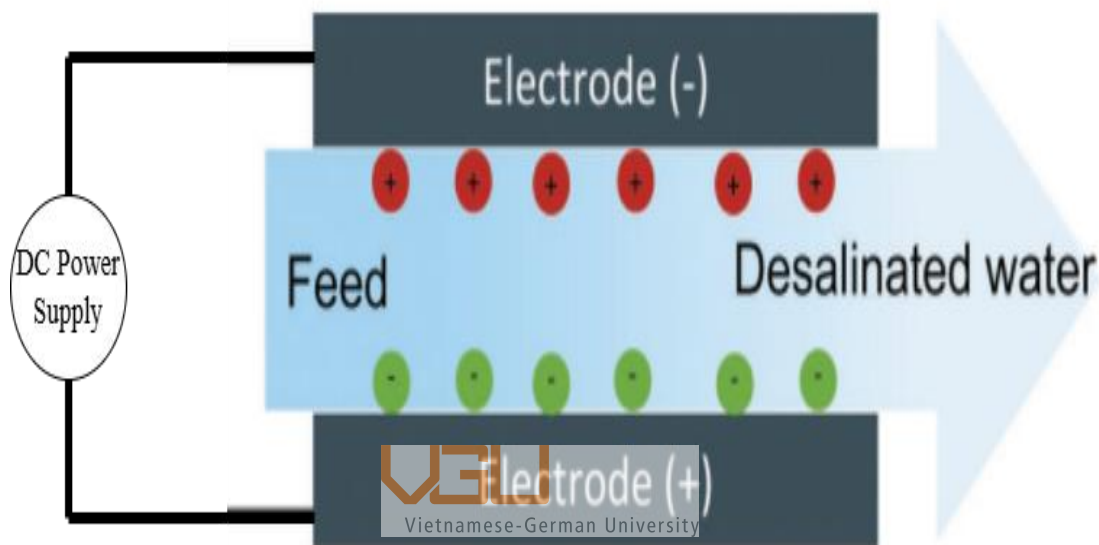


Figure 11: Basic CDI working principle [1].

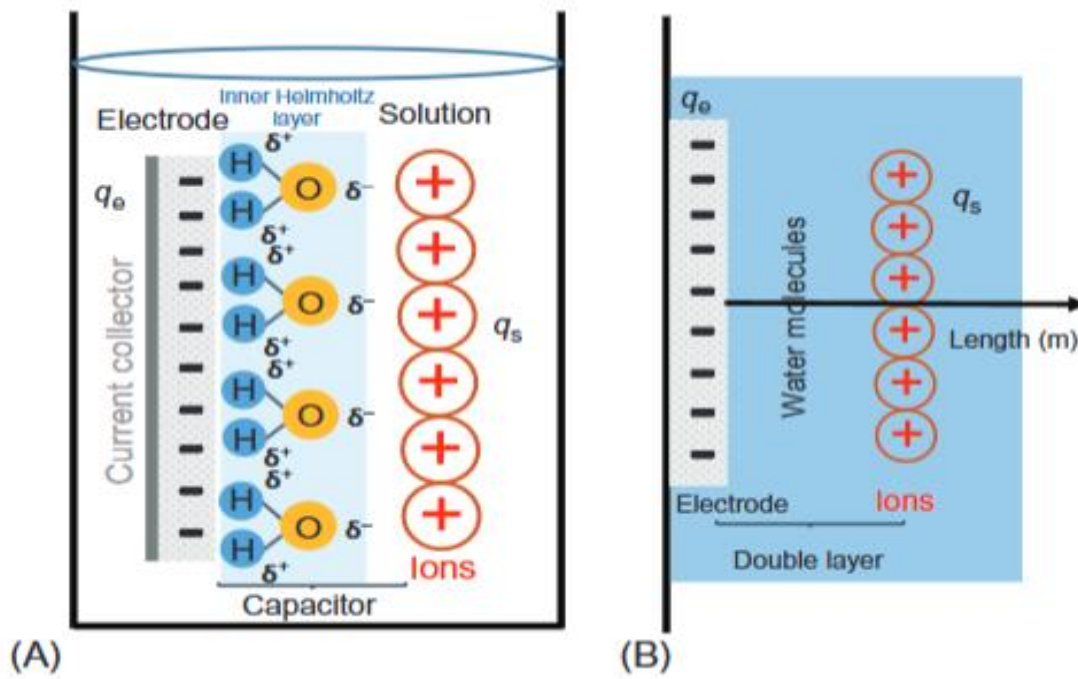


Figure 12: Illustration of the electrical double-layer (EDL) model of Helmholtz and Parrin (a); the potential profile with distance across the electrode-solution interface (b) (Faisal, A., Al Marzooqi, A., Al Amal, A., Al Ghaferi, A., Saadat, I., & Hilal, N., 2014) [3].

In 1924, Stern's model provided a detailed explanation by integrating both the Helmholtz-Perrin and Gouy-Chapman models, presenting them as a combination of two capacitors connected in series, and the total capacitance being expressed as the sum of individual capacitances, as illustrated in equation 1, as indicated in a study conducted by Soujit Sen Gupta, Md Rabiul Islam, and Thalappil Pradeep in 2018 [1].

$$\frac{1}{C} = \frac{1}{C_H} + \frac{1}{C_G} \quad (1)$$

with $C_H = \frac{dq}{dU} = \frac{\epsilon\epsilon_0 A}{d}$, in which suggested that capacitance does not change with potential;

$$\text{And } C_G = \left(\cosh(ze_0\phi M) \frac{1}{2kT} \right) \left(\frac{\sqrt{(2\epsilon\epsilon_0 z^2 e_0^2 c_0)}}{kT} \right), \text{ in which } z \text{ is an integer, } e_0 \text{ is the ionic}$$

cloud charge, ϕM is the potential difference, k is the Boltzmann constant, T is the temperature of the solution, and c_0 is the ionic concentration in the solution.

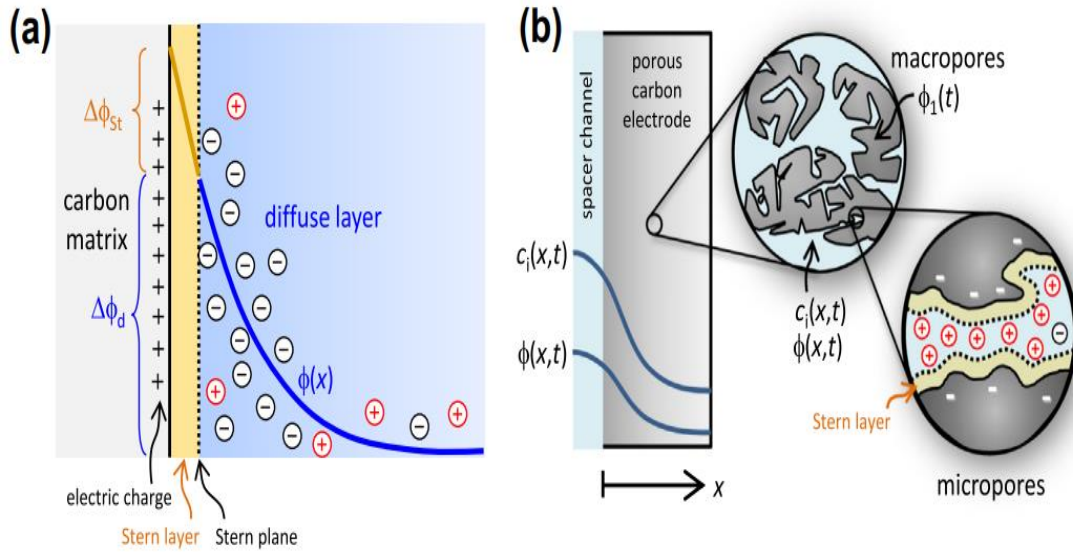


Figure 13: Depiction of charge and ion storage mechanism in porous electrode; (a) EDL with diffuse layer modelled based on Gouy-Chapman-Stern theory for a single planar EDL, (b) The Donnan model describes the mechanism of EDL within the micropores, this model suggests that both macropores and micropores contain electrolyte with an average ion concentration locally. The larger and continuous interparticle pores (macropores) facilitate salt transportation through the electrode's thickness and maintain charge neutrality with a salt concentration denoted as 'c'. Conversely, the excess ionic charge in the intraparticle micropores is balanced by electrical charge present in the carbon matrix [5].

Figure 13 pointed out the classical electrostatic double layer (EDL) theory for capacitive systems that are ideally polarizable. In this hypothetical framework, it is hypothesized that the charge present is solely attributed to the electronic charge within the carbon electrode, as well as the ionic charge stemming from ions present in the aqueous phase, thereby perfectly offsetting each other. Nevertheless, this simplification overlooks the potential surface charge arising from chemical ion adsorption or carbon redox reactions, which are vital considerations in a more comprehensive analysis of the electrostatic double layer phenomenon [5].

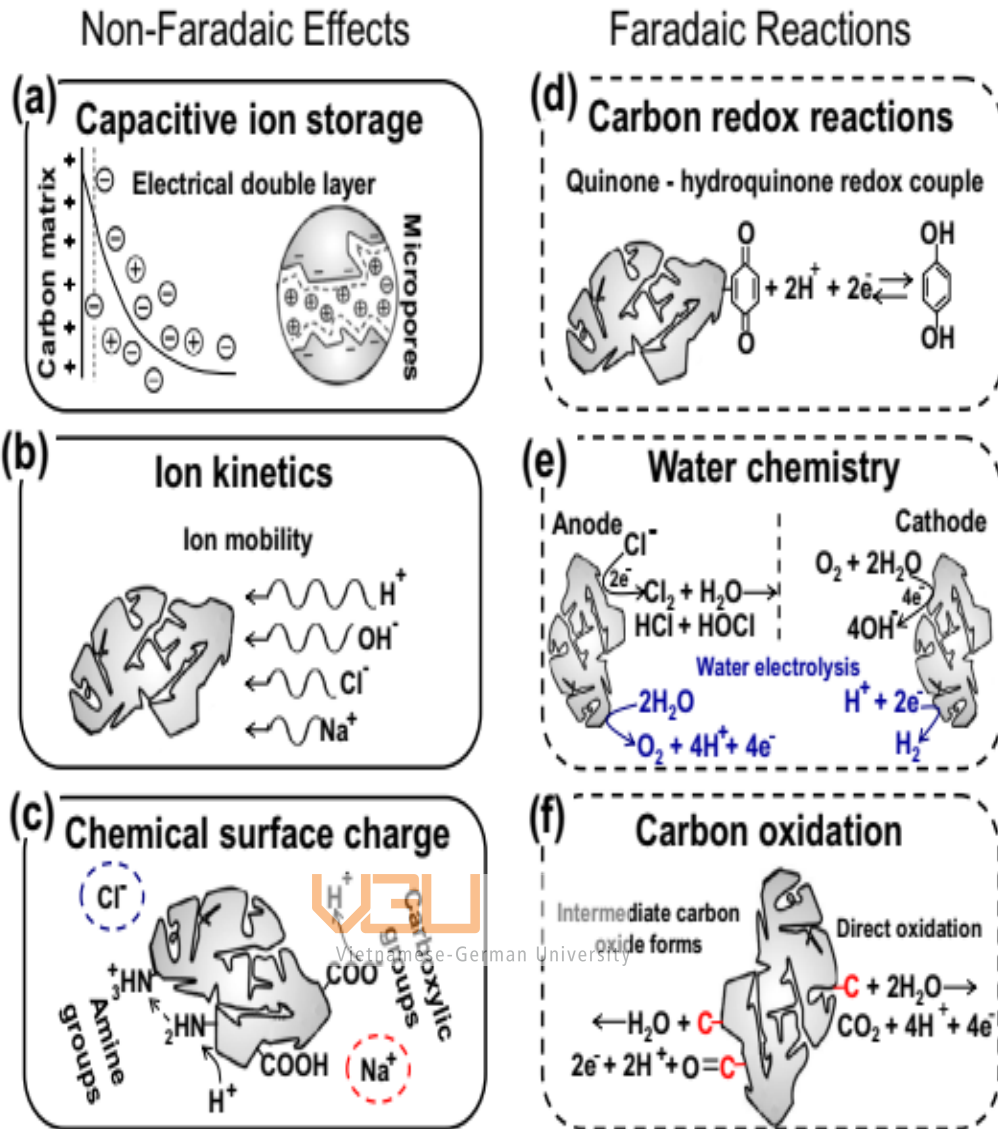


Figure 14: Significant electrochemical reactions and processes occurring within CDI electrodes. These effects, denoted as (a-c), fall under the category of non-Faradaic processes, which involve charge separation and accumulation without the involvement of redox reactions. In contrast, effects (d-f) are characterized as Faradaic processes, where electron transfer reactions occur at the electrode-electrolyte interface, leading to changes in oxidation states and the formation of new chemical species [5].

The non-Faradaic phenomena associated with porous carbon-based capacitive deionization (CDI) have been the subject of thorough research and modeling for numerous years, leading to the identification of three primary classifications [1].

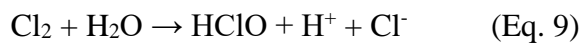
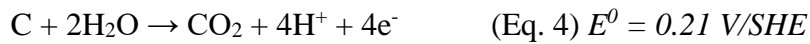
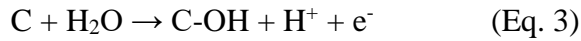
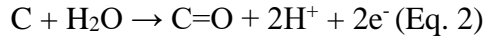
(a) *Capacitive ion storage* entails the occurrence of creating an electrical double layer (EDL), which involves the electrostatic capture and capacitive storage of ions in the diffuse layer established adjacent to the carbon interface when a charge

is applied. The development of this capacitive EDL serves as the fundamental mechanism propelling the Capacitive Deionization (CDI) process forward, showcasing the pivotal role played by this phenomenon in the efficient removal of ions from water sources.

(b) *Ion kinetics* pertains to the impact of the variation in the mobility of different ions on the formation of the Electric Double Layer (EDL). These charged particles, specifically salt ions, protons, and hydroxyl ions are shifted from the spacer channel through macro- and mesopores into the micropores. In Capacitive Deionization (CDI), rapid ion transport rates are crucial; however, the high mobility of H^+ and OH^- ions in comparison to salt ions could potentially influence the process. This influence may result in diminished salt adsorption in the EDLs and lead to pH fluctuations when the adsorption of H^+ differs from that of OH^- .

(c) The term "*chemical surface charge*" refers to the presence of charged groups located at the interface between carbon and the electrolyte, groups that play a crucial role in determining the natural charge of carbons. Typically, these groups consist of carboxylic entities that impart a negative charge to the material or amine-functionalities that give the material a positive charge. In cases where both types of groups are present on the carbon surface, the material exhibits amphoteric behavior. This suggests that based on the local pH in the area of the carbon surface, the material might be either positively or negatively charged. Consequently, a specific pH threshold is present beyond which the material exhibits a negative charge and below which it exhibits a positive charge, essentially establishing a pH point of zero charge for the carbon. The charge exhibited by these groups is influenced by factors such as their intrinsic pH-value and the local pH conditions within the micropores (Biesheuvel, P., Fu, Y., & Bazant, M., 2012) [7]. The pH levels in the micropores may vary significantly from those in the bulk solution due to differences in the local electrical potential and the rates at which H^+ and OH^- ions move into and out of the pores. Consequently, the charging status of these groups can undergo substantial changes throughout a Capacitive Deionization (CDI) cycle. These alterations in charging status result in a net absorption of H^+ and OH^- ions and lead to fluctuations in pH within the flow channel. Additionally, the fluxes connected to the adsorption and desorption of H^+ and OH^- ions also have a role in the movement of salt ions, a phenomenon that can be examined using the Nernst–Planck–Poisson framework.

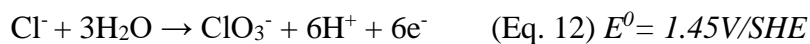
The faradaic reactions occurring at the CDI electrode have detrimental impacts, including a reduction in deionization efficiency and life span, the production of secondary chemicals, as well as a decrease in energy efficiency. These listed reactions pose challenges to the overall performance and longevity of the capacitive deionization process [1].



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$$E^0 = 0.46 \text{ V/SHE}$$



Faradaic reactions, as illustrated in figure 14, have the potential to be subdivided into additional categories, which may assist in elucidating the complexities of these reactions. Further investigation and modeling of these distinct groups are imperative in order to enhance comprehension of faradaic reactions in Capacitive Deionization (CDI). This deeper understanding can pave the way for leveraging faradaic reactions to boost CDI efficiency or mitigate potential risks that could compromise the overall performance of the CDI process.

(d) *Carbon Redox Reactions* refer to the phenomenon where specific carbon surface groups exhibit the ability to alter their redox state without causing any charge separation between the surface and the solution. An example of this concept in carbon chemistry is the alteration of quinone (Q) to hydroquinone (HQ), a process during which two =O bonds within the quinone group on the carbon undergo a reaction involving two

electrons and two protons, leading to the generation of two -OH groups (HQ). The existence of these groups on the carbon surface facilitates the storage of electronic charge in the desalination/release cycle, all achieved without the need for the adsorption of salt ions like Cl^- or Na^+ . Instead, through this mechanism, protons get chemically adsorbed in the cathode as the carbon transitions from Q to HQ. Consequently, the Q-to-HQ reaction has the potential to induce pH variations within the Capacitive Deionization (CDI) spacer channel, thereby influencing the overall performance of the system.

(e) The term “*water chemistry*” serves as a comprehensive umbrella for all electrochemical processes occurring where various components in the water interact at the carbon surface. The resulting products do not remain at the surface but instead dissolve into the electrolyte. Predominantly, these components include water along with its H^+/OH^- charge carriers, Cl^- , and dissolved O_2 . The phenomenon of water splitting, commonly referred to as water electrolysis, is recognized as a limiting factor for the CDI process when voltages exceed the threshold of 1.23 V. Beyond this point, there is a notable risk of experiencing a considerable electrical leakage current, accompanied by the development of hydrogen gas and oxygen gas. Nonetheless, it has been observed that the stringency of this limit is not absolute, as operational efficacy below 1.23 V can be achieved in practical applications. This deviation from the anticipated constraint may be attributed to the non-steady-state nature of the CDI process, leading to localized variations in ion concentrations within the electrode that do not align with the values expected in a free solution. Moreover, an interesting aspect of water chemistry is the chance of the reverse process of water cleavage, where oxygen that is submerged in the water undergoes reduction at the cathode edge. This particular reaction results in an increase in pH levels within the effluent stream, offering a nuanced perspective on the intricate dynamics of electrochemical processes in aqueous environments (Lee, J.-H., Bae, W.-S., & Choi, J.-H., 2010) [8]. The oxidation process of chloride ions that unfolds at the anode is a fundamental step in various chemical reactions, and it plays a significant role in the overall chemical transformations happening. Furthermore, the subsequent disproportionation of chlorine gas into hypochlorite compounds is another essential aspect to consider when examining the complex mechanisms of these reactions [8].

(f) Finally, the concept of *carbon oxidation* entails the potential scenario where carbon not only acts as a catalyst for chemical reactions as outlined in (e), but also undergoes sacrificial participation in a conversion mechanism, undergoing progressive

oxidation and, as posited, potentially being electrochemically transformed into CO_2 , thereby resulting in a reduction in electrode mass and the deterioration of CDI efficiency.

Using low voltage in capacitive deionization (CDI) is highly essential due to the fact that higher voltages have the potential to trigger Faradaic reactions, specifically oxidation and reduction processes. These reactions not only result in the deterioration of the electrode materials but also lead to co-ion repulsion and a decrease in charge efficiency (CE) (Yu-Jeng, Lin., Chau-Chyun, Chen., 2023) [10]. The Faradaic reactions induced by higher voltages can give rise to the formation of surface oxide layers, which subsequently elevate the sheet resistance and impede electronic charge utilization (Johan, Nordstrand., Esteban, Toledo-Carrillo., Joydeep, Dutta., 2023) [11]. Consequently, this adversely impacts the salt separation performance of the CDI cell. Furthermore, the maintenance of low voltage levels plays a critical role in attaining a harmonized ion adsorption process. Elevated voltages can lead to charge leakage and an imbalance in the removal of anions and cations, thereby further compromising the effectiveness of the overall process (Qinghao, Wu., Dawei, Liang., Shanfu, Lu., Jin, Zhang., Haining, Wang., Yan, Xiang., Doron, Aurbach., 2021) [12]. The application of low voltage not only aids in enhancing the energy efficiency and cost-effectiveness of CDI as a desalination technology but also strategically positions it against alternative methods such as reverse osmosis and distillation, particularly for the treatment of brackish water with low to moderate salt concentrations (Amit, N., Shocron., Imri, Atlas., Matthew, E., Suss., 2022) [13]. Moreover, considerable progress has been achieved in the advancement of sophisticated electrode materials and cell architectures that improve ion selectivity and adsorption capacity while operating at reduced voltages. This, thereby, contributes to the improvement of the overall performance and stability of CDI systems. Consequently, the deliberate choice of employing low voltage, which is typically at the range of voltage difference between 0.8-2.0 V [9], in CDI serves as a strategic measure to prevent adverse Faradaic reactions, thereby safeguarding the durability and efficiency of the electrodes as well as the desalination process.

In summary, ions, as well as various other charged entities, are attracted through electrostatic forces and are firmly attached to the inner surface of the electrode, which holds an opposite charge. The anionic species are selectively taken in by the positively charged electrode, whereas the cations are drawn to and accumulate on the negatively charged electrode. Accordingly, the makeup of the electric double layer (EDL) bears a

net charge, showcasing similarities to the charging mechanism seen in double-layer capacitors (DLC). This phenomenon highlights the intricate interplay between surface chemistry and electrostatic interactions in the electrochemical systems (Yu., M., Volfkovich., 2018) [1]. When the electrode surface becomes saturated with ions, it becomes necessary to initiate a process of reversed voltage discharge (RVD) or halting/zero voltage discharge (ZVD) in order to restore its functionality, thereby enabling the system to generate purified water as well as a highly concentrated solution with practical applications [1].

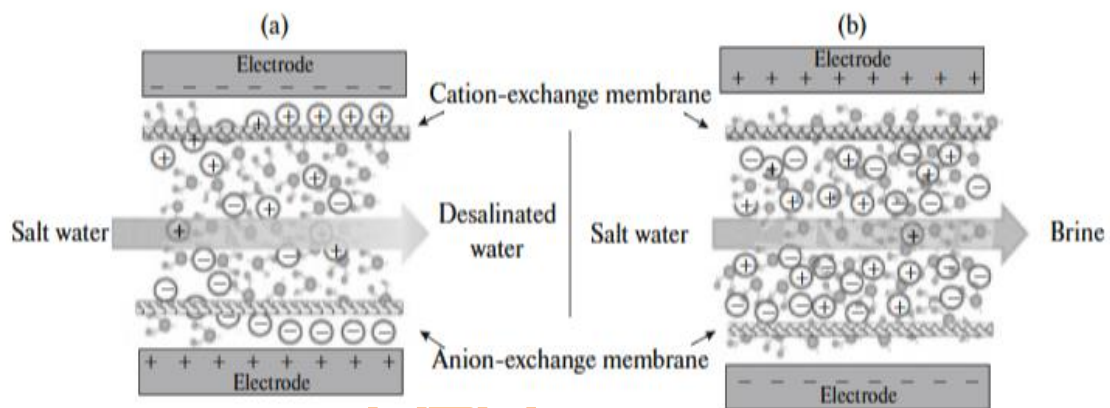


Figure 1: Stages of deionization (a) and regeneration (b) in a Membrane CDI (MCDI) [1].

The main benefit, which CDI technology introduces, is a low consumption of electrical energy; comparing with its main competitor in the industry like Reverse Osmosis (RO), CDI only use a third of RO's energy expenditure (Zhao, R., Porada, S., Biesheuvel, P. M., & van der Wal, A. (2013) [2].

Table 6: Specific energy expenditure for the main methods of water desalination [3].

Method of water desalination	Specific energy expenditure, kWh/m ³ of water
Multistep distillation	10-58
Reverse Osmosis	2-6
Electrodialysis	0.4-8.7
Capacitive deionization	0.1-2.03

In the study conducted by Andelman, M. in 2011, it was determined that the energy required for salt removal in capacitive deionization (CDI) closely approaches the thermodynamic minimum essential for desalinating highly concentrated solutions like sea

water [4]. Capacitive deionization of water offers numerous benefits compared to other water purification techniques. These perks consist of decreased maintenance expenses, which are calculated to represent around one-third of the expenditures associated with reverse osmosis systems, long-lasting cyclability of electrode materials, and the existence of chemically stable components that block the intrusion of contaminants into the treated water stream. Moreover, CDI exhibits versatility in its ability to operate at various levels of ion removal and pure water production, while also minimizing pore clogging from deposits. The cutting-edge technology integrated into CDI systems suggests a promising future with anticipated enhancements in efficiency over the coming years. However, CDI has a disadvantage of low efficiency, and thus pushing for new design for improvements.

In the illustration provided in figure 14, it is evident that during the concentration stage (also known as regeneration), the energy has the capability to be reused, thereby offsetting a portion of the energy required for the charging process. Consequently, the overall deionization energy can be defined as the discrepancy between the total work involved in the charging process and that in the discharging process, as expressed by equation 2 and figure 14:

$$W_{cdi} = W_{charge} - W_{discharge} \quad (2)$$

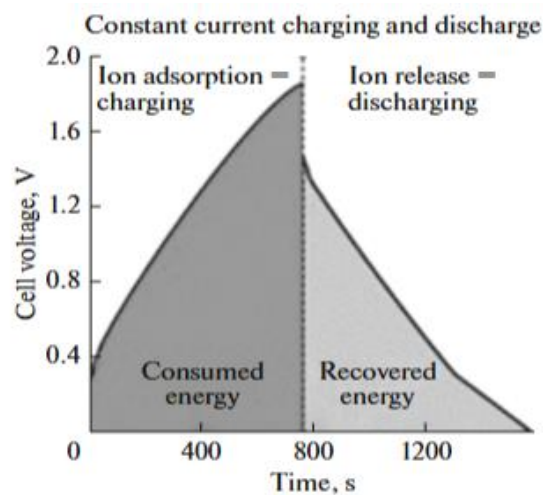


Figure 1: Illustration of voltage over time in the stages of charging and discharge [1].

This fundamental equation encapsulates the essence of energy dynamics in the context of deionization processes, shedding light on the intricate interplay between charging, discharging, and energy recycling mechanisms [1]. During the charging process,

the double-layer capacitor is charged and consequently discharged in the regeneration phase, in which produced treated water and brine, respectively.

The approach to charging and discharging in the electro-chemical cell utilized for CDI can be performed in two different manners: either the potentiostatic mode where the voltage (U) is kept constant, or the galvanostatic mode where the current (I) is regulated at a steady level. In the potentiostatic mode, the amount of energy associated with deionization during charging and concentration during discharging can be determined using a specific formula

$$W = U \int_{t_1}^{t_2} I dt \quad (3)$$

whereas in the constant current mode, the energy is calculated as follows:

$$W = I \int_{t_1}^{t_2} U dt \quad (4)$$

where t is time.

Further studies have been conducted, extensively looking into working parameters and improvements to CDI's design, as this technology opens a new realm for desalinating saline water. Over time, both the academic and industrial fields have realized the potential for this technology and increasingly placed more effort into realizing the CDI technology as a practical desalinating method.

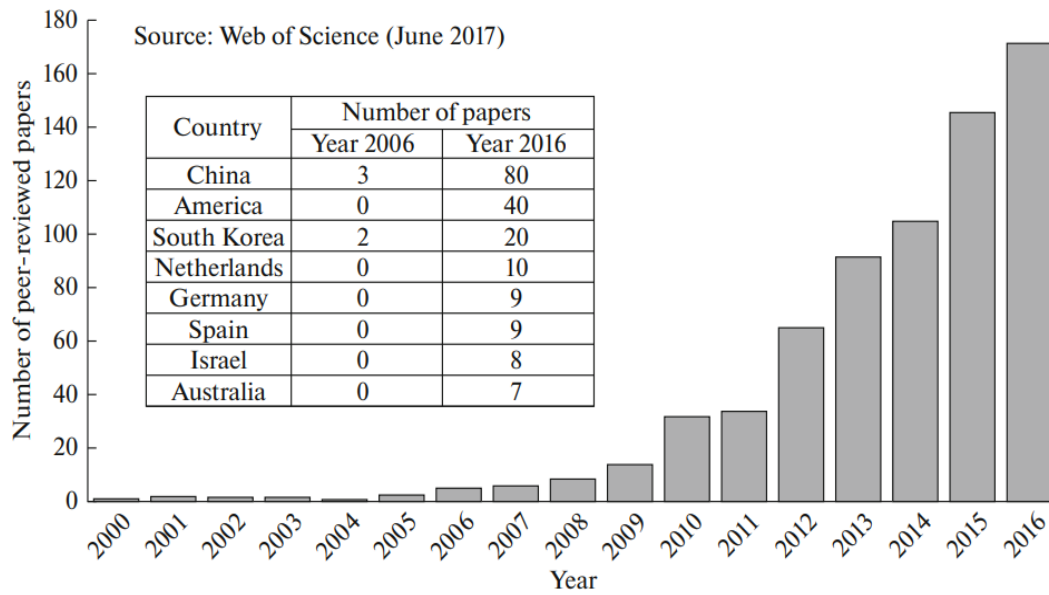


Figure 1: The number of reviewed papers in the CDI field since 2000 till 2016 and the comparison of the number of publications related to CDI in several country [1].

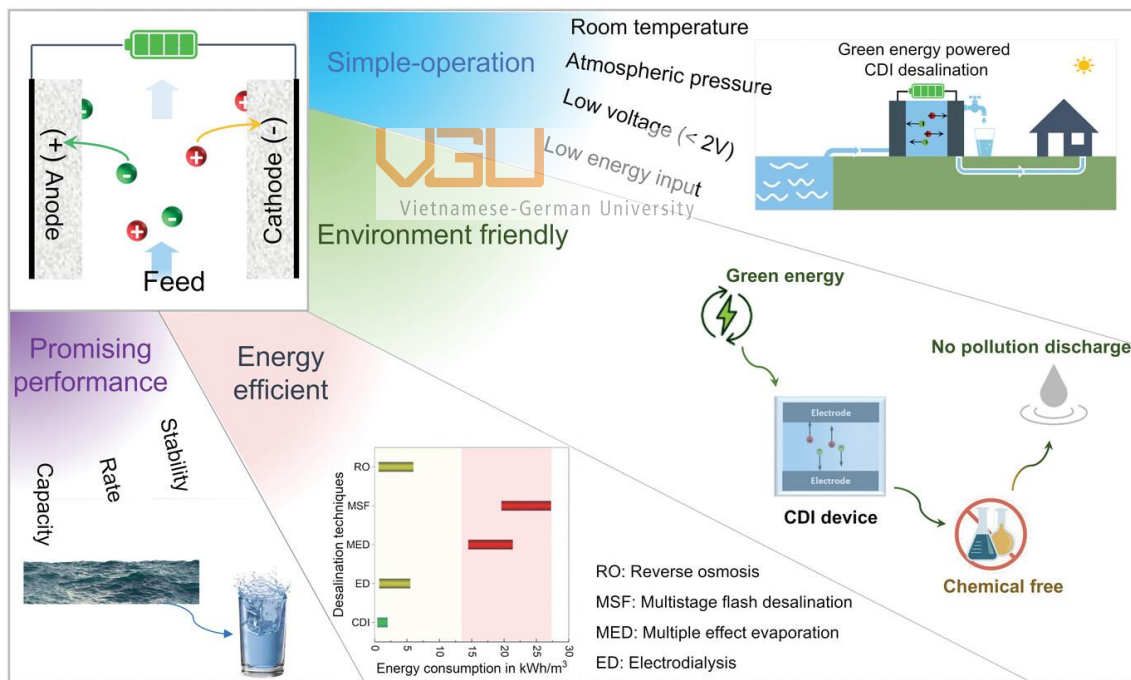


Figure 1: Summarization for CDI technology perks: simple-operation, environment friendly, energy efficient, and promising performance [9].

2.3.2. CDI's configurations

The study of CDI cell architectures has gathered interest in recent years within the academic community. There are two primary categories of electrode cell architectures that have been extensively explored: static and flowable electrodes CDI. The static

electrode architecture encompasses both flow between electrodes and flow-through electrodes, as well as membrane CDI. Development for flow between electrode CDI has introduced inverted CDI (i-CDI), which used a surface-modified anode [5]. The arrangement of the flow electrode comprises the uninterrupted introduction of a carbon slurry to aid the desalination process of the feed water, enabling a consistent flow of the slurry to efficiently eliminate impurities and salt ions from the water stream, thereby enhancing the efficiency of the desalination process with the use of this innovative electrode design (Suss, M., Baumann, T. F., Bourcier, W. L., Spadaccini, C., Stadermann, M., Rose, K., & Santiago, J. G., 2012) [14].

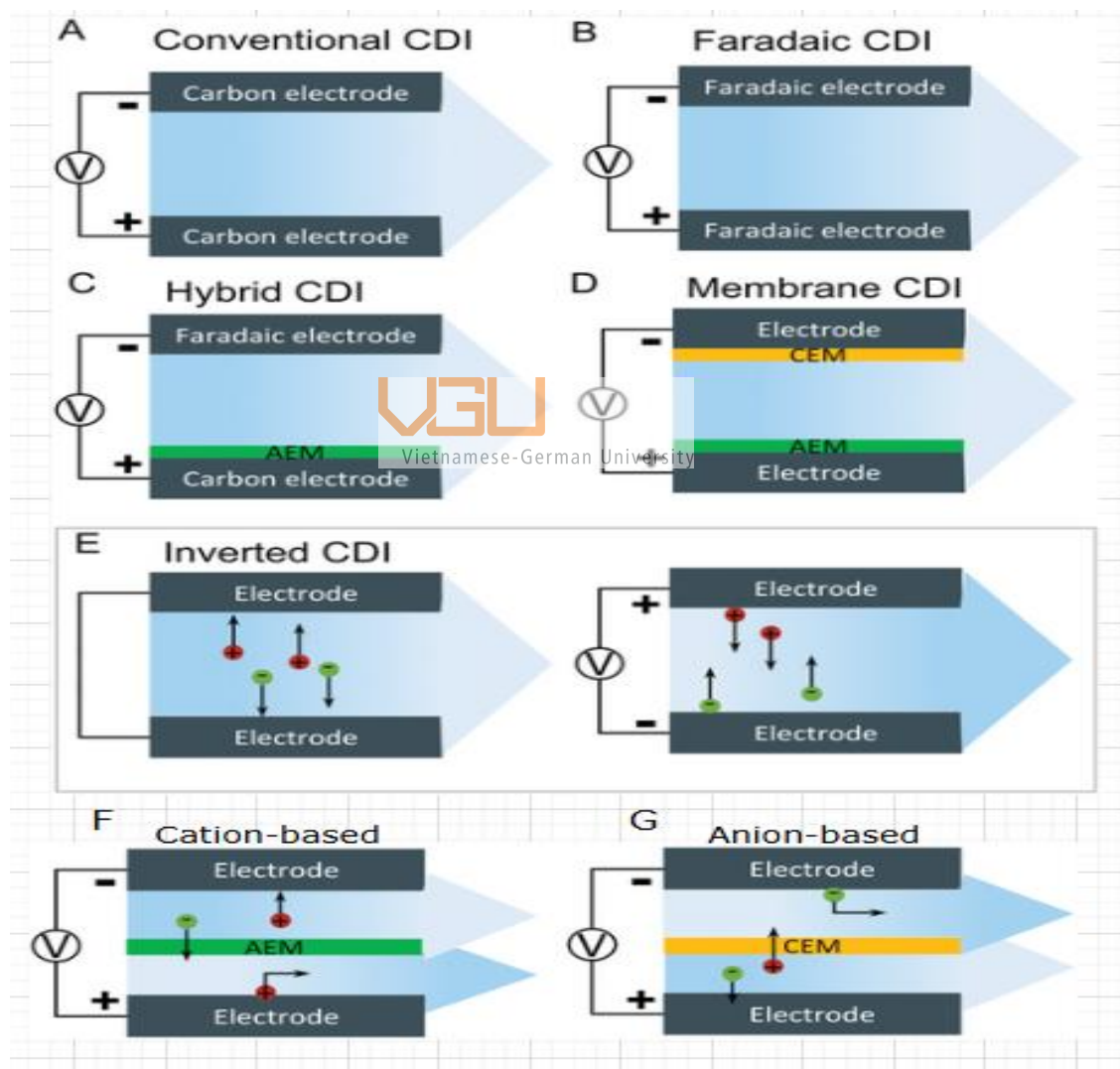


Figure 1: Variant designs introduce additional enhancements to the field of static electrode capacitive deionization [9].

The implementation of membrane-assisted capacitive deionization (MCDI) has demonstrated substantial enhancements in the salt absorption capacity (SAC) and charge

efficiency (CE) in comparison to the conventional CDI systems utilizing solely porous carbon electrodes [9]. The introduction of cation-exchange membrane (CEM) and anion-exchange membrane (AEM) serves to ease the possible occurrence of faradaic reactions taking place at the electrodes' surfaces and to prevent co-ion repulsion, a commonly encountered obstacle in conventional capacitive deionization (CDI) processes. However, the MCDI technology is faced with challenges due to its complex design, particularly the positioning of membranes between anodes and cathodes, which ultimately hinders MCDI's ability to resist organic matter and results in a higher overall cost for the system (Silvia, Ahualli., Sergio, Orozco-Barrera., María, M., Fernández., Ángel, V., Delgado., Guillermo, R., Iglesias., 2019) [15]. This complexity in design not only impacts the system's efficiency in handling organic substances but also raises concerns about the economic feasibility of implementing MCDI technology in various applications. Inverted-CDI (I-CDI) is a unique variation of the conventional capacitive deionization process that employs electro-adsorption in a different manner. Typically, conventional CDI systems generate treated water and high concentration water during the charge and discharge phases, respectively. On the contrary, I-CDI operates with reversed polarity and surface charged electrodes, resulting in negatively charged anodes and positively charged cathodes. As a result, I-CDI exhibits a desorption effect during the charging phase and absorption during the discharge phase, offering a novel approach to water treatment processes (Xiaoping, Che., Shiyong, Wang., Changping, Li., Gang, Wang., Chengxu, Li., Shuaifeng, Wang., Duangzheng, Li., Jieshan, Qiu., 2019) [16]. The research conducted by Xin, Gao, Ayokunle, Omosebi, James, Landon, and Kunlei, Liu in 2018 has investigated the effectiveness of Inverted-CDI in reducing the oxidation of carbon electrodes, which is the main factor in degrading conventional CDI's performance, as indicated in their study [17].

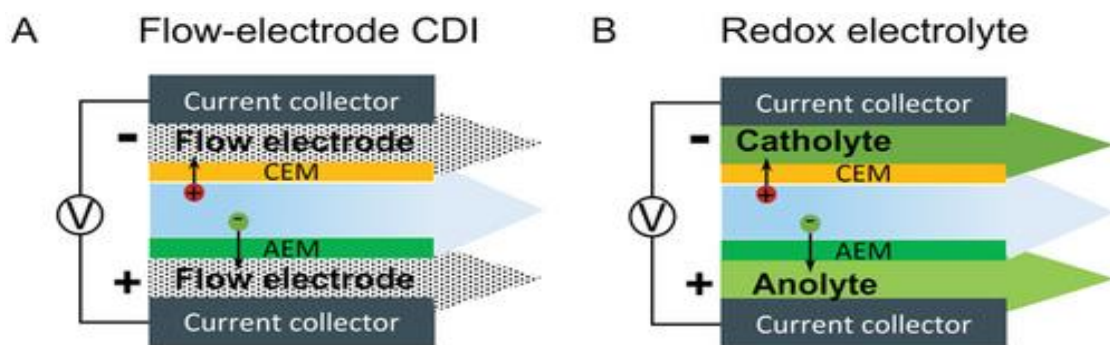


Figure 1: Examples of Flowable CDI (FCDI) system configuration [9].

Unlike the traditional capacitive deionization (CDI) technique which depends on fixed electrodes, the Flowable Capacitive Deionization (FCDI) method employs dynamic electrodes that are often composed of activated carbon suspensions or catholyte/anolyte, moving within the system. This design enables uninterrupted operation and eliminates the requirement for frequent regeneration, offering a unique advantage over conventional CDI systems. The use of flowable electrodes in FCDI not only boosts the efficiency of ion removal through increased ion adsorption capacity but also enhances the sustainability of the deionization process by allowing continuous circulation and operation, thereby reducing the need for frequent regeneration in comparison to static CDI devices as ref [18-19] pointed out. This innovative technology offers significant benefits in the treatment of high-concentration saline water due to its capability to carry out both desalination and metal recovery concurrently through the integration of an ion enrichment module. The amalgamation of this module allows the system to efficiently segregate salts from water while also retrieving precious metals, rendering it a highly effective and sustainable remedy for water treatment procedures [9]. The electrochemical properties of FCDI cells are influenced by a range of factors, like the quantity of activated carbon in the flow-electrode and the flow rate, both of which are essential in adjusting the internal resistance, charge transfer resistance, and ion adsorption resistance of the system (W.-J., Gong., Ya, Yang., Haiqing, Chang., Tianyu, Wang., Heng-Chia, Liang., 2022) [20].

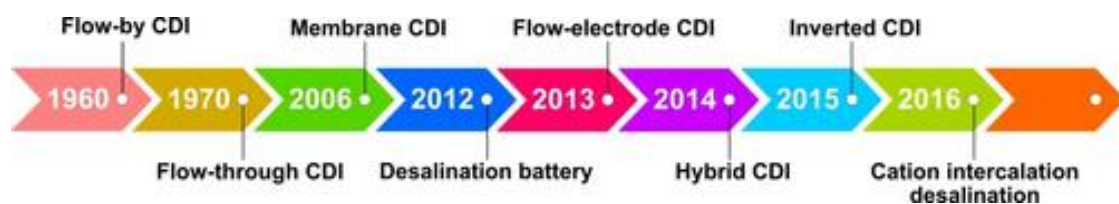



Figure 1: Progress in CDI architecture designs over years (Kumar et al., 2023) [25].

Table : A benefits and drawbacks summary of CDI's architecture class [25].

CDI's architectures	Benefits	Drawbacks
Flow-between electrodes	The design is uncomplicated, with minimal energy usage, yet capable of efficiently removing high amounts of salt.	The susceptibility to fouling and chemical contaminations is characterized by a low resistance.
Flow-through electrodes	The efficiency of salt removal is high.	Elevated feed pressure is necessary and necessitates

		the use of sizable macropore electrodes.
Inverted-CDI	Long-term operational stability and efficient removal of ionic pollutants.	Limited working voltage window.
Membrane CDI	The system exhibits low energy usage, a high capability to remove salt, an extended lifespan of the electrodes, and the ability to function effectively across a broad spectrum of flow rates.	Less proficient in high salinity conditions, prone to fouling, and characterized by high operational costs.
Desalination battery	Efficient energy conversion, minimal operational expenses, and ability to be scaled.	Limited desalination capacity, as well as lower efficiency compared to other energy storage systems.
Hybrid CDI	The ability to remove high levels of salt, along with being energy efficient and capable of scaling up.	The design is intricate, costly, and offers limited resistance to fouling.
Flowable electrodes CDI	High salinity levels result in a high efficiency of desalination processes.  Vietnamese-German University	The saturation level of a carbon slurry could be managed through the optimization of both the flow rate and the size of the channel.

2.3.3. Electrode materials and important metrics for CDI

Capacitive deionization (CDI) technology heavily depends on the progress and optimization of electrode materials to improve the efficiency, stability, and scalability of the desalination process. Recent progress in this field has been primarily directed towards the exploration and enhancement of different carbon-based materials owing to their exceptional electrical conductivity, expansive specific surface area, and remarkable chemical durability. Noteworthy is the use of porous carbon nanomaterials, including the amalgamation of single-layer graphene oxide (SGO) with nitrogen-doped porous carbon (NPC) and activated carbon fiber (ACF), which has shown significant enhancements in electrochemical efficacy and salt adsorption capacity (SAC) (Chunyu, Chen., Li, Men., A, Liu., Si, Yu., Jian, Guo, Zhou., Zihan, Wei., Dianchun, Ju. (2022) [21]. These advancements highlight the promising potential of carbon-based materials in revolutionizing the landscape of electrode materials for capacitive deionization technology. Furthermore, porous carbon materials derived from biomass and activated

using potassium hydroxide (KOH) have shown to possess elevated specific surface areas and favorable ion storage properties, thus establishing them as economically viable and environmentally sustainable alternatives for various applications (A, Boyle., Hadiji, Yukari, Nagao., 2022) [22]. The incorporation of ion-exchange membranes into membrane capacitive deionization (MCDI) setups, employing substances such as montmorillonite and hydrotalcite, has significantly improved ion specificity and charge effectiveness (CE), dealing with challenges like co-ion repulsion and Faradaic responses [12]. Faradaic electrode materials, which rely on Faradaic reactions to capture ions, present distinctive prospects for applications in high salinity streams, enabling greater capacities for salt removal and enhanced energy efficiency in contrast to conventional carbon electrodes (Qian, Li., Yun, Zheng., Dengji, Xiao., Tyler, Or., Rui, Gao., Zhaoqiang, Li., Ming, Feng., Lingling, Shui., Guofu, Zhou., Xin, Wang., Zhongwei, Chen., 2020) [23]. Furthermore, it has been demonstrated in recent studies that graphene oxides modified with nitrogen and titanium dioxide exhibit remarkable capabilities when utilized in saline environments, showcasing elevated levels of specific capacitance and consistent desalination efficacy (Khalil, Abdelrazek, Khalil., Nasser, A.M., Barakat., Moaeed, Motlak., Fahad, S., Al-Mubaddel. (2020) [24]. These findings highlight the potential of such composite materials in addressing challenges related to water desalination processes.

To comprehend the materials requirements, the following enumeration presents a crucial set of parameters that determine the desalination performance capability of a material intended for utilization as an electrode material in the process of water desalination through Capacitive Deionization (CDI) technology, which is an essential aspect of studying desalination processes:

- Salt absorption capacity (SAC, mg/g) refers to the quantity of salt ions that are taken in by the electrode per gram of the electrode, as illustrated in Equation (5).

$$SAC = \frac{\{Q \int (C_o - C_e)dt\}}{m_{electrode}} \quad (5)$$

Where, the symbol Q represents the volumetric flow rate of effluent, expressed in milliliters per minute, whereas C_o and C_e denote the initial and effluent salt concentrations, respectively, measured in grams per liter. The variable $m_{electrode}$ signifies the mass of electrode material, in grams, that captures salt ions during the process of water desalination.

- The Average Salt Absorption Rate (ASAR) refers to the salt absorption capacity of the electrode material in relation to the duration of the desalination process, typically measured in minutes, as represented by equation (2).

$$ASAR = \frac{SAC}{\Delta t} \quad (6)$$

Where Δt is desalination process time.

- The charge efficiency (CE) of an electrode can be described as the equilibrium salt adsorption divided by the electrode charge, as illustrated in the equation.

$$CE = \frac{\{zFQ \int (C_0 - C_e)dt\}}{\int Idt} \quad (1)$$

The variable z represents the quantity of charges carried by the ions, F denotes the Faraday constant, and I stands for the electric current measured in Amperes.

- Desorption capacity (DC) is an important indicator in CDI evaluating metrics, as shown in equation (1).

$$DC = \frac{\{(C_e - C_d)\}}{m_{electrode}} \quad (1)$$

- Electrode regeneration efficiency is also vital to CDI performance, it is calculated as listed equation (1).

$$ERE = \frac{SAC_1}{SAC_n} \quad (1)$$

With, 1 denotes the initial concentration and n is the n^{th} cycles.

Table 1: Several metrics of modified activated carbon (AC) [].

AC materials	Specific surface area (SSA) (m ² /g)	Specific absorption capacity (SAC) (mg/g)	Cycle performance (%)
N-doped AC fiber (NPC@ACF)	1098	14.36	n.a
Ni/PPOGrCNT	n.a	19.7	67
AC doped by Fe, N, P (FeNPCs)	n.a	40.42	n.a
AC doped with Prussian blue (PB-AC)	n.a	24.4	95.11
Modified MOF-5 using graphene C-MOF@G	933.72	n.a	n.a

TiO ₂ doped with NTs	n.a	13.11	n.a
Activated graphene combined with graphene aerogels	1401.53	26.33	97.2
Coffee nutshell	323	n.a	n.a
Palm tree leaflets	604.3	5.38	n.a
AC derived from coconut and activated with CO ₂ (AC-CO ₂)	2128	17.5	n.a
AC-P	1710	18	n.a
AC-N ₂	467	10	n.a
AC-P-CO ₂	2617	27.5	n.a
Bitter tea	870	n.a	n.a
Palm shell waste	874	n.a	n.a
Date palm fronds free (nanoparticle-ACNP)	n.a	6.3	n.a
Date palm fronds free (unparticle-UnACNP)	n.a	0.032	n.a

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C. UF-CDI integration for enhanced desalination

Advantages and limitations in the context of saline intrusion

Ultrafiltration emerges as an extremely beneficial pretreatment technique for various water treatment systems, including desalination plants as outlined in this thesis. The process's efficacy in eliminating substantial amounts of suspended solids, bacteria, and high-molecular-weight substances plays a crucial role in minimizing the occurrence of organic fouling observed in NF membranes [1]. Consequently, this leads to a notable improvement in the overall performance and longevity of the desalination setup. Conversely, in practical scenarios, Capacitive Deionization (CDI) presents a range of unforeseen occurrences, such as its vulnerability to organic fouling on electrode surfaces following prolonged exposure to wastewater and susceptibility to damage from specific solids present in water sources [2]. Due to these challenges, CDI cannot function effectively as a standalone system but rather necessitates integration with other highly efficient pretreatment methods like ultrafiltration to optimize its performance. This examination delves into the practical application of CDI in addressing complex water sources, particularly in regions such as Vietnam. Both CDI and UF do not require a high degree of pressure for operation within a desalination framework; the combination of these methodologies has the potential to enhance the desalination performance, specifically in a brackish water setting such as Vietnam, which is grappling with significant saline intrusion issues as highlighted in the introductory section of this scholarly article. The Vietnamese Mekong Delta (VMD) is facing notable impacts, especially with regards to salinity intrusion, which has been worsened by changes in upstream inflows and increasing sea levels. This has resulted in elevated salinity levels and prolonged intrusion distances, further complicating the freshwater estuaries in the region [3]. Also, the problem of groundwater salinization is a pressing issue, with high salinity levels observed several kilometers inland, a phenomenon driven by groundwater extraction practices and the complex dynamics of regional water flow, resulting in the substantial movement of saline water from upper to lower aquifer layers [4].

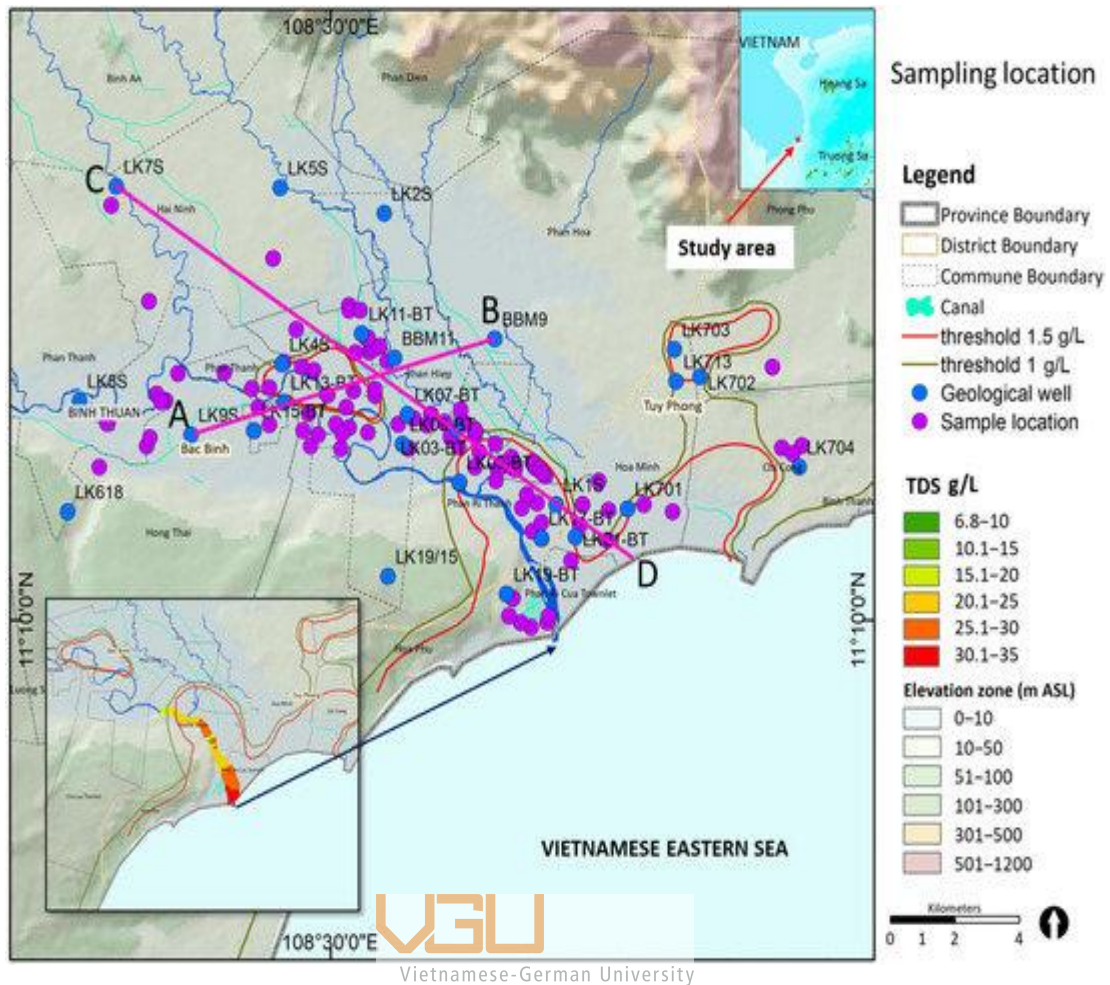


Figure 1: The study area's location, encompassing the topography of the region, the specific sites where samples were collected, and the measurement of Total Dissolved Solids (TDS) in the Phan Ri River as it flows into the East Sea during the summer season of 2019 [5].

A UF combined with CDI desalination system has the potential to effectively tackle the challenges associated with complex water sources, as highlighted in the discussion. The system has the capability to generate desalinated water that is subsequently stored in both wells and groundwater, which have been subject to salinization due to the impact of saline intrusion in the VMD. According to predictions, the system is expected to have the capacity to remove solvent ions that contribute to the overall TDS level, thereby rendering the water unsafe for human consumption, agricultural activities, and dairy farming. The rationale behind the integration of these two technologies lies in the synergistic relationship between them; while UF can reduce the risk of scaling and fouling on the electrodes within the CDI system and eliminate certain larger ions, CDI specializes in the extraction of the primary ions crucial for the desalination process.

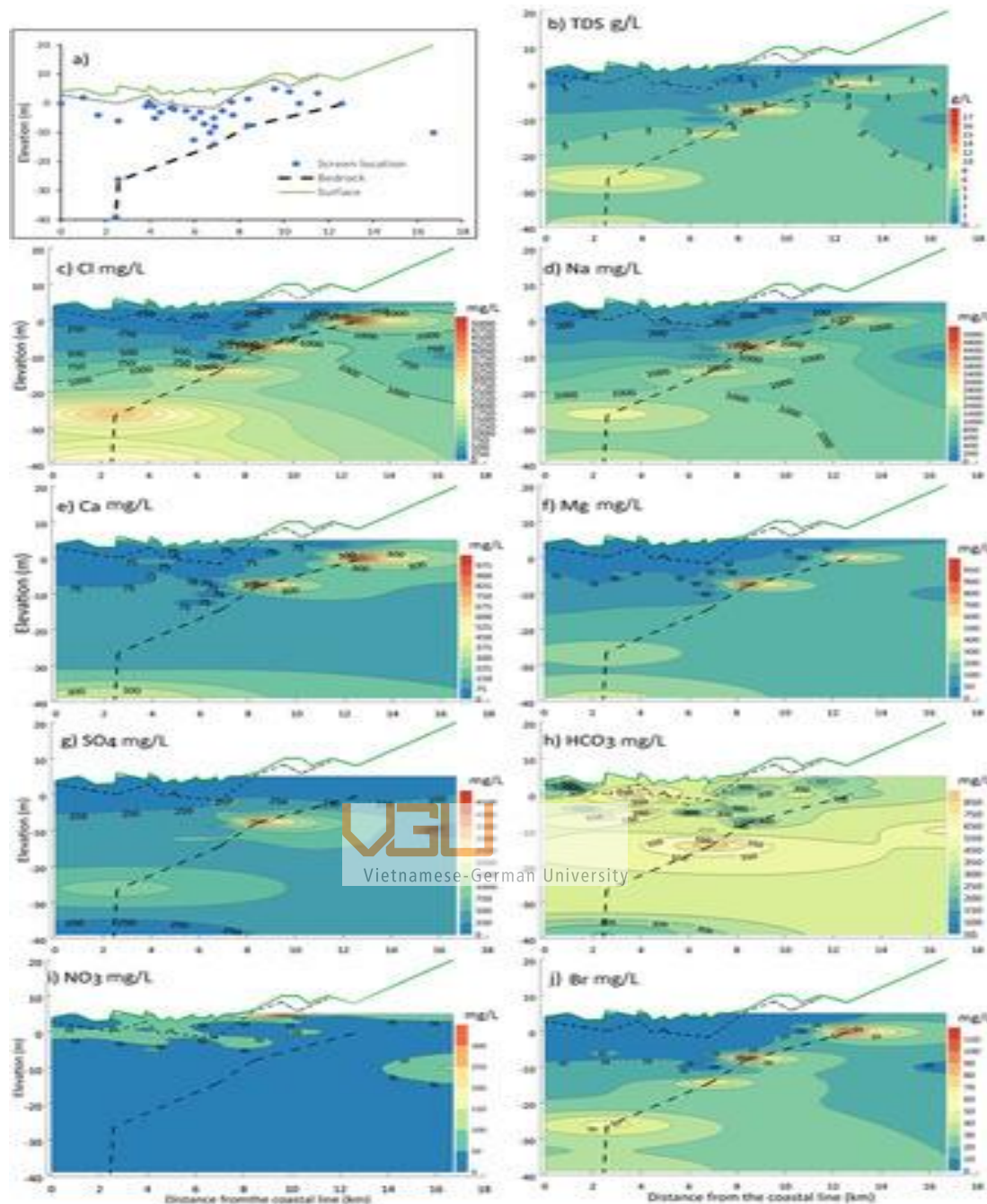


Figure 1: (a) Vertical positions of well screens are shown along the CD profile in Figure 1. The thick black dashed line represents the bedrock surface, the green line indicates the surface elevation line, and the thin black line shows the water table elevation in the wells; (b-j) Interpolation of Total Dissolved Solids (TDS) and ion concentration from water samples is carried out along profile CD [5].

Nevertheless, when it comes to these categories of technology, both Capacitive Deionization (CDI) and Ultrafiltration (UF) encounter challenges in terms of operational efficiency when confronted with the treatment of highly saline water, thereby rendering

them susceptible to issues related to scaling and fouling, which are essentially inevitable drawbacks within the realm of water treatment methodologies. This issue becomes particularly accentuated when addressing the purification of water featuring intricate and varied sources within the geographical context of Vietnam, characterized by a prevalent presence of heightened turbidity levels and a diverse array of contaminants.

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D. Water quality monitoring sensors in desalination systems

Importance of real-time data collection for Vietnamese conditions

For standard water treatment plants, the need for implementing a monitoring system becomes apparent when striving to enhance both the efficiency of the system and its adherence to regulatory standards. This requirement is underscored by findings from a comprehensive study conducted in 2023, which revealed that the integration of a real-time monitoring system holds the promise of significantly enhancing the overall

operational effectiveness and simplifying the process of monitoring and regulating the various qualitative aspects of water for its designated uses [1]. Continuously monitoring key parameters like pH, temperature, salinity, and contaminant levels, which are essential for ensuring the quality of the produced water and maintaining desalination performance for such a system [1]. The implementation of inexpensive and energy-efficient sensor technology aimed at assessing various parameters related to the quality of water can provide additional support for enhancing the real-time monitoring functionalities within water treatment systems designed for multifaceted applications. This integration of low-power sensors not only contributes to the overall improvement of system reliability but also facilitates a more user-centric approach, thereby ensuring greater efficiency and ease of operation [2].

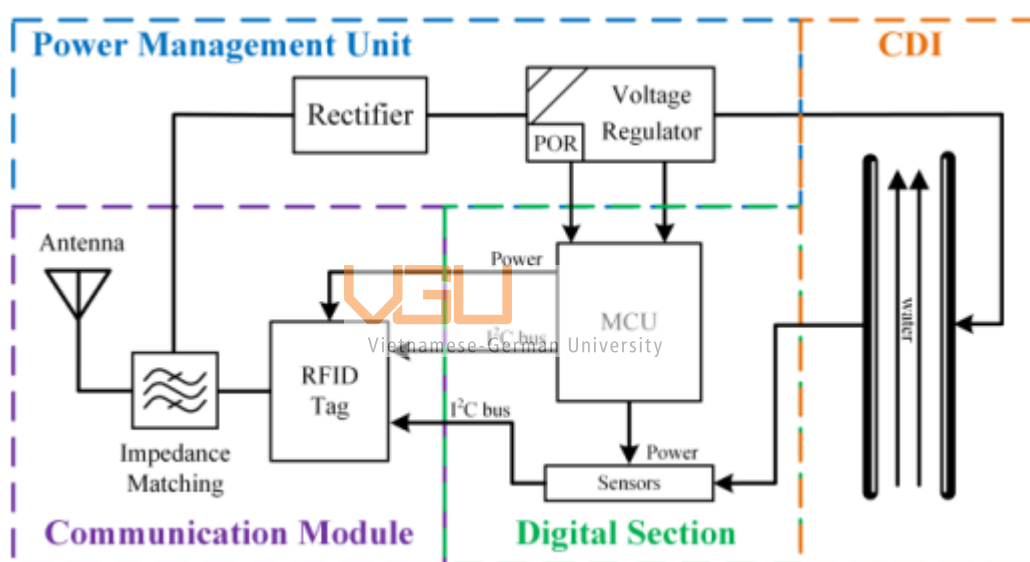


Figure 1: Labortory CDI system with integrated Internet of Things (IOT) monitoring system [2].

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III. Methodology

A. System Design

Description of UF membrane module and selection process, considering Vietnamese water characteristics

The ultrafiltration (UF) membrane is accessible in a range of materials and pore sizes, however, in the context of the imagined desalination system, it is vital for the UF membrane to operate as a critical barrier that serves as a defense mechanism against the invasion of large particles, viruses, bacteria, and substantial ions. The rationale behind this specific role assigned to the UF membrane is rooted in the fact that UF membranes possess the inherent capability to effectively purify the influent stream by removing a significant proportion of contaminants and ions even before the treated effluent proceeds towards the Capacitive Deionization (CDI) unit. Such a strategic configuration enables the CDI system to primarily concentrate on the selective extraction of targeted ions such as sodium (Na^+) and chloride (Cl^-) ions, thereby mitigating the likelihood of detrimental effects on the electrode's surface arising from undesired side reactions, which predominantly occur at the interface of the electrodes. Moreover, the UF technology exhibits remarkable efficiency in combating turbidity and Natural Organic Matters (NOMs), which are known culprits contributing to the fouling of CDI electrodes through the formation of a thin film layer on the electrode surface, consequently impeding the efficiency of the adsorption and desorption processes.

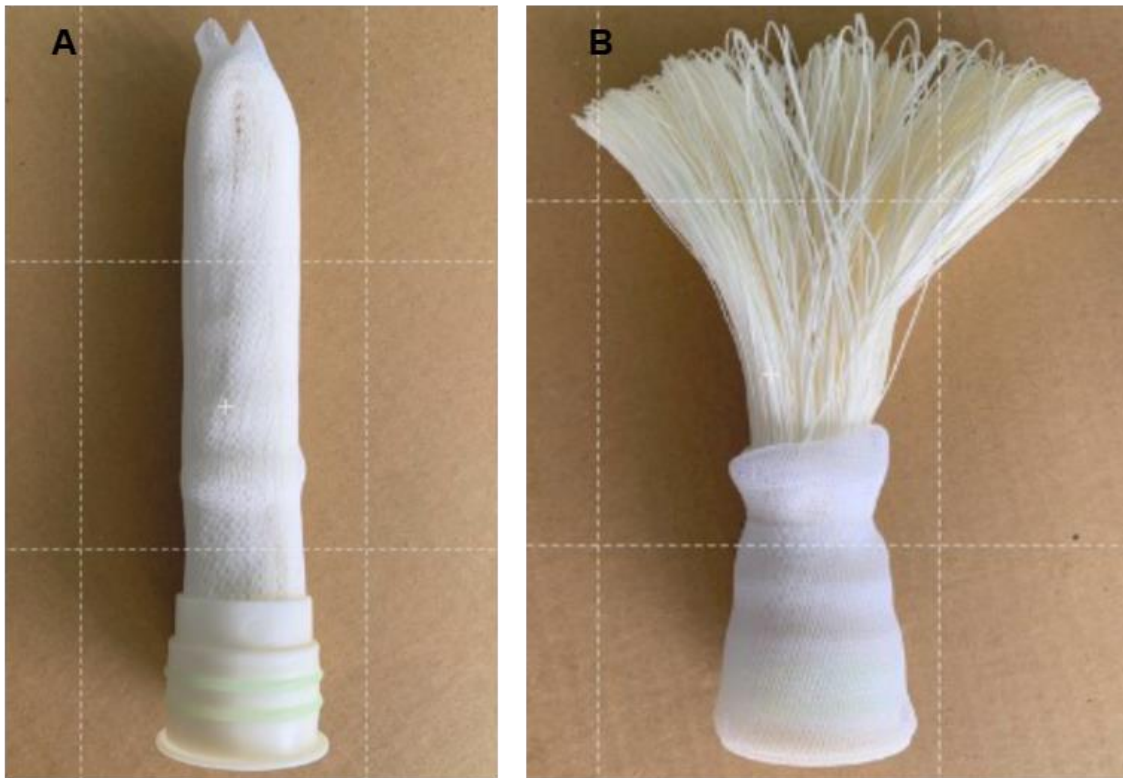


Figure 1: Chosen UF membrane (China).

The selected UF membrane for this particular project features hollow polyvinylidene fluoride (PVDF) fibers characterized by a pore size measuring 0.01 micrometers and wrapped by a plastic mesh, a configuration commonly seen in UF membrane technology. This specific membrane design is anticipated to serve as an effective and efficient barrier, effectively inhibiting the passage of contaminants and a small part of saline components typically present in water sources throughout Vietnam. Although recent advancements have introduced various novel membrane technologies for UF, the conventional material arrangement tailored for this membrane application has demonstrated its effectiveness in the context of household water treatment facilities. This membrane, which is manufactured in China and conveniently procured through online platforms, has consistently shown satisfactory performance in treating water for domestic use.

Design of CDI unit with chosen electrode configuration

The pivotal role in the contribution to the success of the system is held by the design of the CDI unit, which necessitates a smart and carefully thought-out design that facilitates the installation of electrodes and their current collectors, a crucial aspect that was taken into account during the meticulous designing process. In the intricate task of designing a CDI cell, especially when dealing with a high-performance CDI unit boasting a high

number of electrode pairs, the designer is met with the imperative task of contemplating how the water flow is regulated and how it interacts within the confines of the CDI cell and with the electrodes themselves. Upon the entry of effluent water into the cell, a deliberate design choice ensures that it cascades down to the lowermost pair of electrodes initially, gradually permeating the cell in a methodical manner, thereby optimizing the time that the effluent water is in contact with the electrodes for the essential processes of adsorption and desorption to take place thoroughly. The importance of the spacer and the gap between the electrodes should not be underestimated in their impact on the performance of the CDI system; thus, it is vital to understand that the cell features a high-performance mesh-type spacer to efficiently enable the flow of water between the electrodes, thereby increasing the overall operational efficiency of the system.

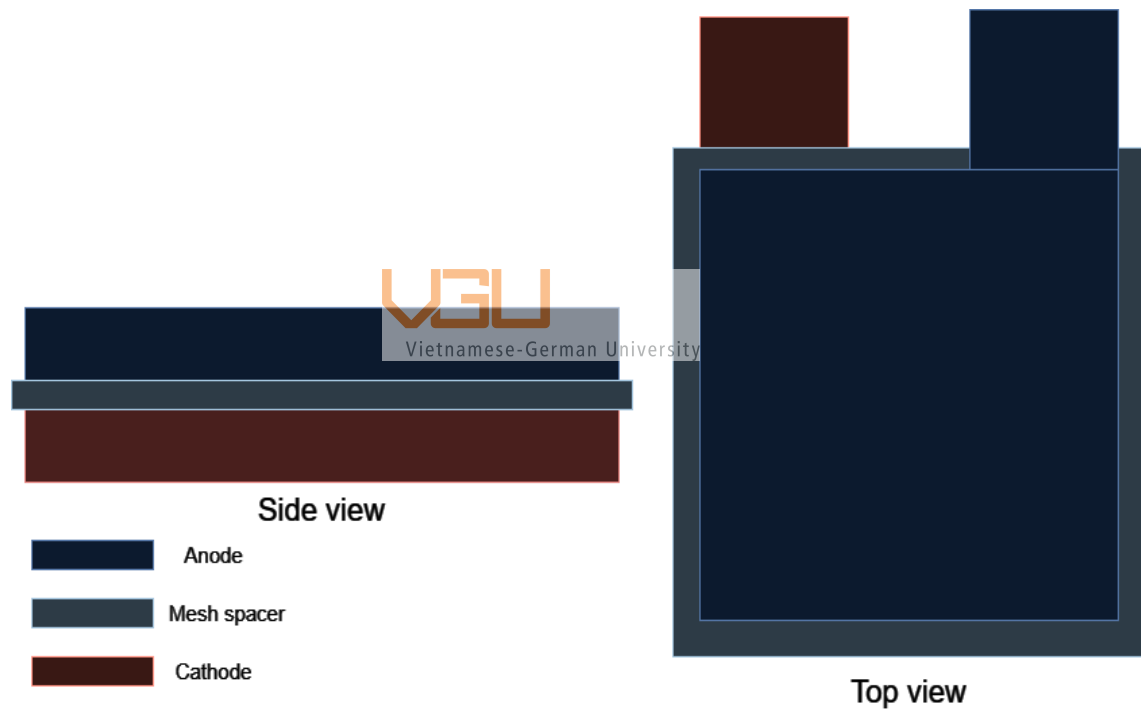


Figure 1: Electrodes configuration.

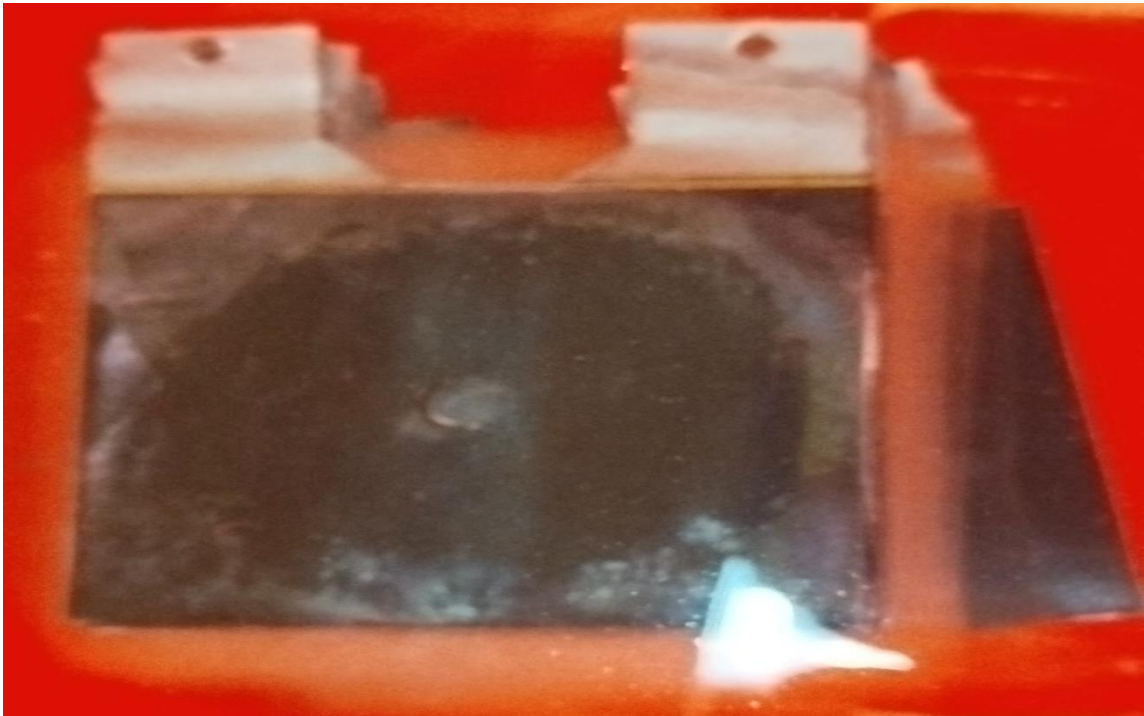


Figure 1: Prepared electrodes with Activated Carbon Electrodes from Siontech (Korea).

The purchase of electrodes made of Activated Carbon from Siontech (Korea) along with a spacer, was carried out in accordance with the specified procedure and subsequently arranged in the prescribed configuration. The operational surface featured a layer of activated carbon applied onto a graphite sheet measuring 10cm by 10cm, with surplus graphite allocated for connection purposes with the current collectors. The empty space situated between the two current collectors facilitates the passage of treated water to exit the CDI cell, thereby establishing a suitable water circulation system within the cell and the electrodes.

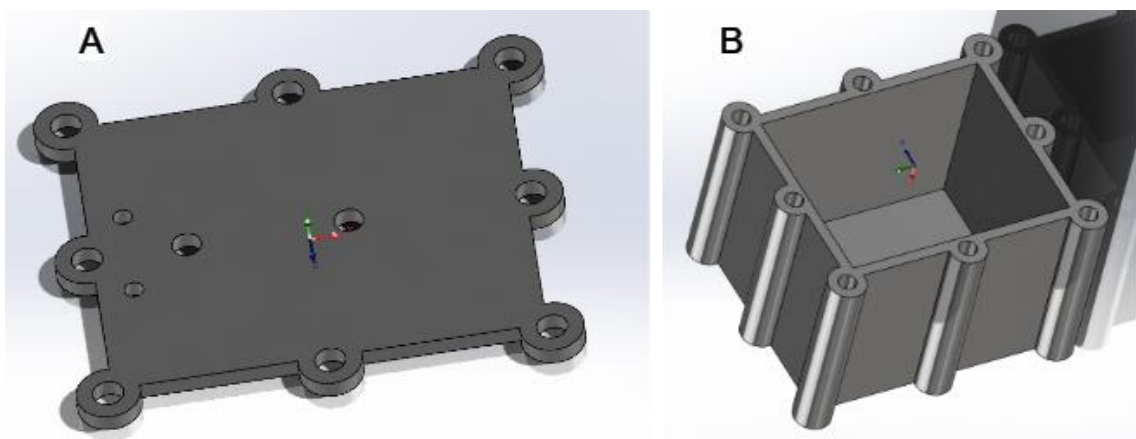


Figure 1: CDI cell 3D design. (A) top mount with water inlet/outlet and current collector mounts; (B) cell's body.

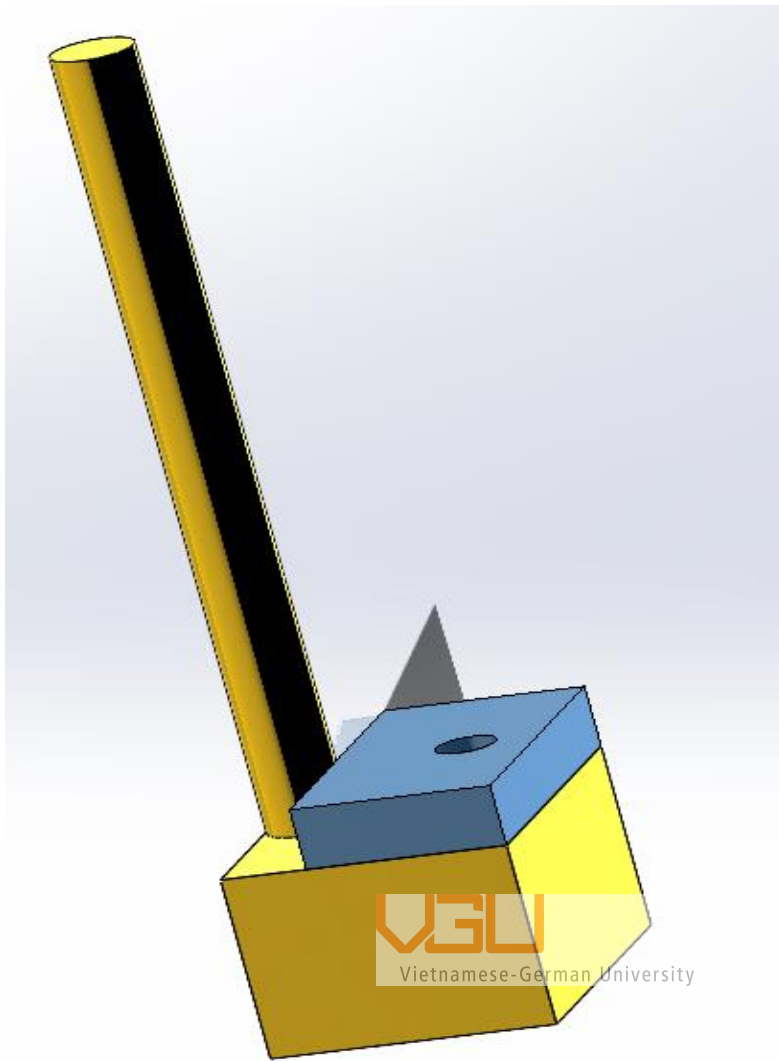


Figure 1: The design of the current collector in three dimensions is being illustrated. The component colored in blue serves as the security cap, while the yellow component functions as the current collector body. The current collector would be constructed from copper to optimize electrical conductivity, is responsible for securing the graphite sheet using M4 bolts and the security caps.

Integration of pre-treatment (if applicable) and post-treatment options to address potential challenges from saline intrusion

When formulating a water treatment system aimed at addressing a diverse array of water sources, it is imperative to incorporate a thorough pretreatment strategy. In the context of the system put forth in this thesis, it is recommended to make use of the initial three pretreatment cartridges; these cartridges are specifically designed to address issues such as odor and NOM. The primary activated carbon cartridge aims to tackle odor and NOM,

while the subsequent two cartridges utilize microfiltration technology with a filtration size of 10 microns and 5 microns respectively.

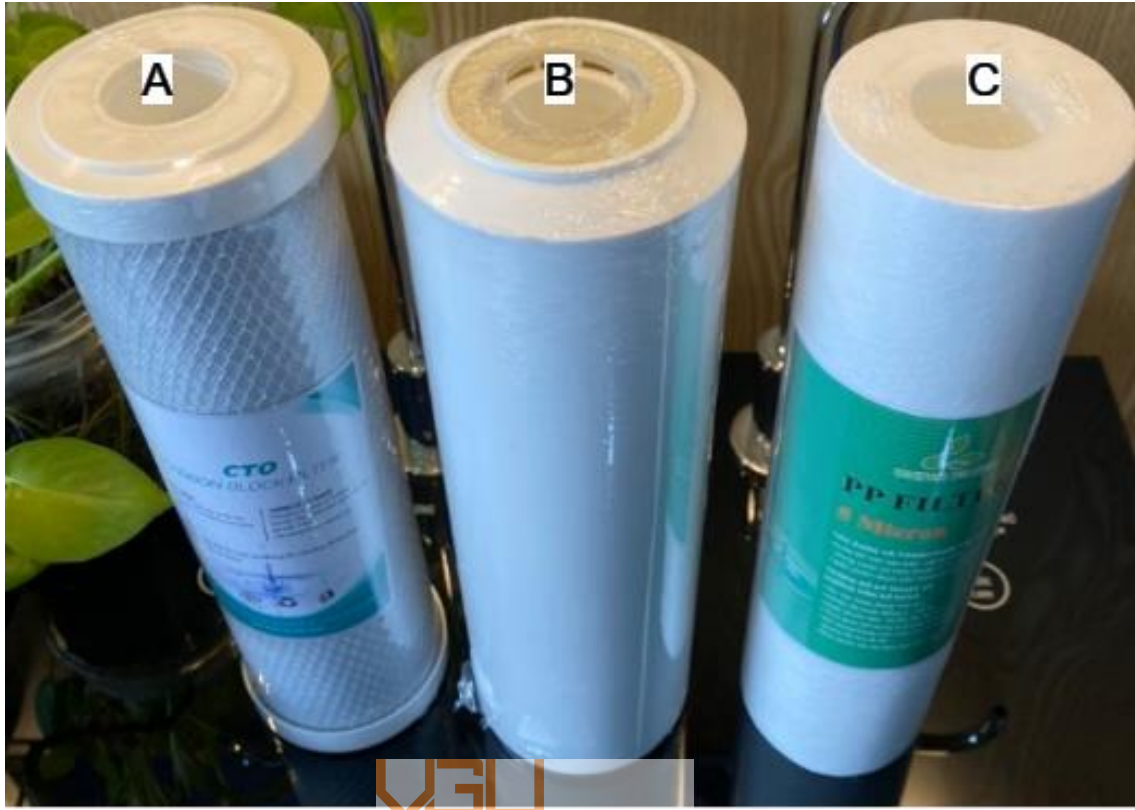


Figure 1: Pretreatment with (A) activated carbon sludge, (B) 10 microns filtration cartridge, (C) 5 microns filtration cartridge.

Although the UF technology possesses the ability to eliminate bacteria and viruses due to its minute physical pore size, it is important to note that the Capacitive Deionization (CDI) method also exhibits disinfection effects for water by leveraging electrical energy to directly extract salt ions present in the water. Nevertheless, it is crucial to consider the integration of a post-treatment system in the desalination process in order to comply with the established standards for producing potable water. In order to effectively address the presence of organic matter, viruses, and bacteria, it is advisable to contemplate the inclusion of an Ultraviolet (UV) system as a post-treatment component within the desalination framework. However, when integrating a UV sterilization system into a design, it is imperative for the designer to carefully deliberate upon various key characteristics associated with the system. These factors include, but are not limited to, the recommended flowrate of water through the system and the duration for which the water should be exposed to the UV light within the designated chamber. Such considerations are contingent upon the power output of the UV light source itself, thereby

necessitating a comprehensive understanding of the interplay between these variables in order to optimize the system's efficacy. In this particular case, the selected UV system boasts a rated power output of 11 watts, which further underscores the significance of aligning the system's operational parameters with its intended functionality and performance objectives.



Figure 1: Ultraviolet sterilizer system (China).

Water quality monitoring sensor selection and placement, focusing on parameters crucial for Vietnamese brackish water (e.g., salinity, turbidity)

As expounded upon in the comprehensive analysis of existing literature, the implementation of a system comprising quality indicators for water, exemplified by water sensors, would undeniably offer a substantial enhancement in terms of value to a desalination system. Within the scope of this particular endeavor, a diverse array of

sensors has been meticulously selected and strategically positioned. Presented in the tabular format hereafter is a detailed compilation delineating the sensors, their respective operational voltages and currents, in conjunction with the specific targeted parameters for assessing the quality of water, thereby facilitating a comprehensive understanding of the inherent characteristics of the water undergoing treatment and subsequent production. These sensors are intended to be strategically positioned within two distinct sensor stations, one stationed prior to the commencement of the treatment process and the other stationed subsequent to the completion of the entire desalination system. The integration of all sensors within the system involves establishing a connection to a micro-controller, specifically identified as the Arduino Mega 2560, originating from Italy. Noteworthy for its robust capabilities, the Arduino Mega 2560 is characterized by a substantial array of input and output pins that facilitate the overall functionality of the system. These pins are designed to operate within a voltage range of 5V, thus underscoring the importance of selecting sensors that are compatible with this voltage specification. As a result, sensors featuring a working voltage range spanning from 3.3V to 5V, a common requirement for sensors interfacing with micro-controllers, are deliberately chosen for seamless integration within the system. It should be acknowledged that the sensors mentioned possess the ability to provide both analog signals and digital signals; however, in the context of the current project, analog signals are chosen for use and are transformed into a particular measuring unit by means of careful calibration and programming, ensuring accurate and reliable data collection.

Table 1: List of sensors with their recommended working voltages, currents and measuring quality values.

Sensor's name	Working Voltage (V)	Rated Current (mA)	Measuring value and description
DFR0300	3.3 - 5	n.a	Measuring electrical conductivity helps quantify the ions in water. A sensor provides a voltage output which is subsequently transformed into Total Dissolved Solids (TDS) unit (parts per million) through programming. This sensor is designed for high-range applications and can effectively measure elevated levels of electrical conductivity.

SEN0244	3.3 - 5	n.a	This sensor is designed to gauge electrical conductivity, specifically within a limited range of conductivity levels (0-1000ppm)
DS18B20 waterproof	3.3 - 5	1000	The sensor is responsible for converting an analog signal (voltage drop when current travels through a resistor) into temperature units through programming.
DIYMore pH-4502C	3.3 - 5	n.a	The sensor is designed to transform voltage within a simulated capacitor in order to provide pH values in the form of voltage output.
LGZD 5VDC	5	30	This sensor is capable of assessing the light dispersion between two ends of the sensor and subsequently providing a voltage output signal.
YF-S401	5-18	n.a	This flowrate sensor has the ability to measure flowrate and total volume through the utilization of the Hall-effect.

Data acquisition and control system (DACS) for sensor integration

The sensors, in their individual capacity, are incapable of functioning independently without the existence of a centralized computing system that is tasked with overseeing, interpreting, and making decisions based on the data received from these sensors. The primary objective of this particular project is to establish an integrated control mechanism for the desalination system, in tandem with a comprehensive data acquisition system. To realize this objective, all the various components involved are interconnected with the Arduino Mega 2560, which assumes the role of the central controlling entity. The advantages of implementing such a system include its user-friendly plug-and-play nature and cost-effectiveness; however, the main obstacles to overcome pertain to the intricate programming requirements and the precise positioning of each component and its corresponding functions.

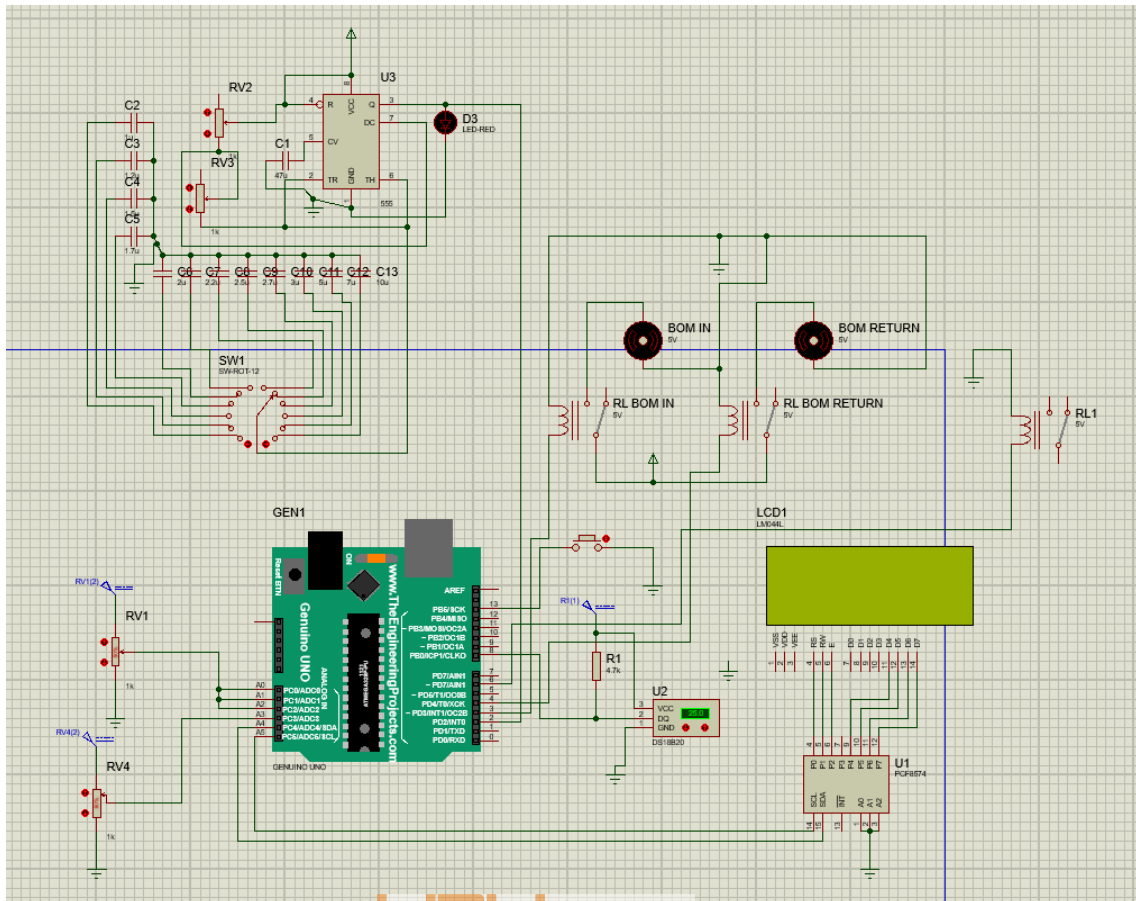


Figure 1: The depiction of an electrical schematic through the utilization of the Prometheus programming application is demonstrated in the visual representation provided. Within this diagram, it is depicted that the Arduino microcontroller is tasked with receiving signals which are subsequently displayed on a 20 by 4 LCD screen while also regulating the power supply directed towards the CDI unit.

B. System Construction

Material selection for corrosion resistance in Vietnamese brackish water conditions

The initial step in the creation of the CDI cell unit involves selecting materials suitable for the operational requirements of the cell and the actual construction process. The CDI cell unit is typically utilized in environments characterized by low pressure, however, due to its interaction with water, it is imperative that the chosen material is resistant to water leakage. Initially, the option of utilizing 3D printing with Polylactic Acid fillet (PLA) was contemplated for the prototype cell fabrication. Nevertheless, upon careful reconsideration of factors such as durability and susceptibility to leaking, the determination was made to manufacture the cell using CNC machining from a Polyoxymethylene (POM) plastic billet with dimensions measuring 150cm by 150cm by 100cm. This strategic choice not only ensured a reduction in construction expenses but also minimized the overall material costs in comparison to the utilization of 3D printing

with PLA. The total cost reduction is about 20% compared with cell made by 3D printing. All the components that come into contact with water have been carefully selected to prevent any undesired side reactions between the water and the materials used in the construction of the tube and sensor stations. The selection process aims to ensure optimal performance and longevity of the equipment in various water-related applications.

Assembly and testing CDI cell

The heart of the desalination system is the CDI cell unit, which consist of 3 main parts: cell body and top mount made from POM, current collectors (mainly made from copper), and the electrodes.

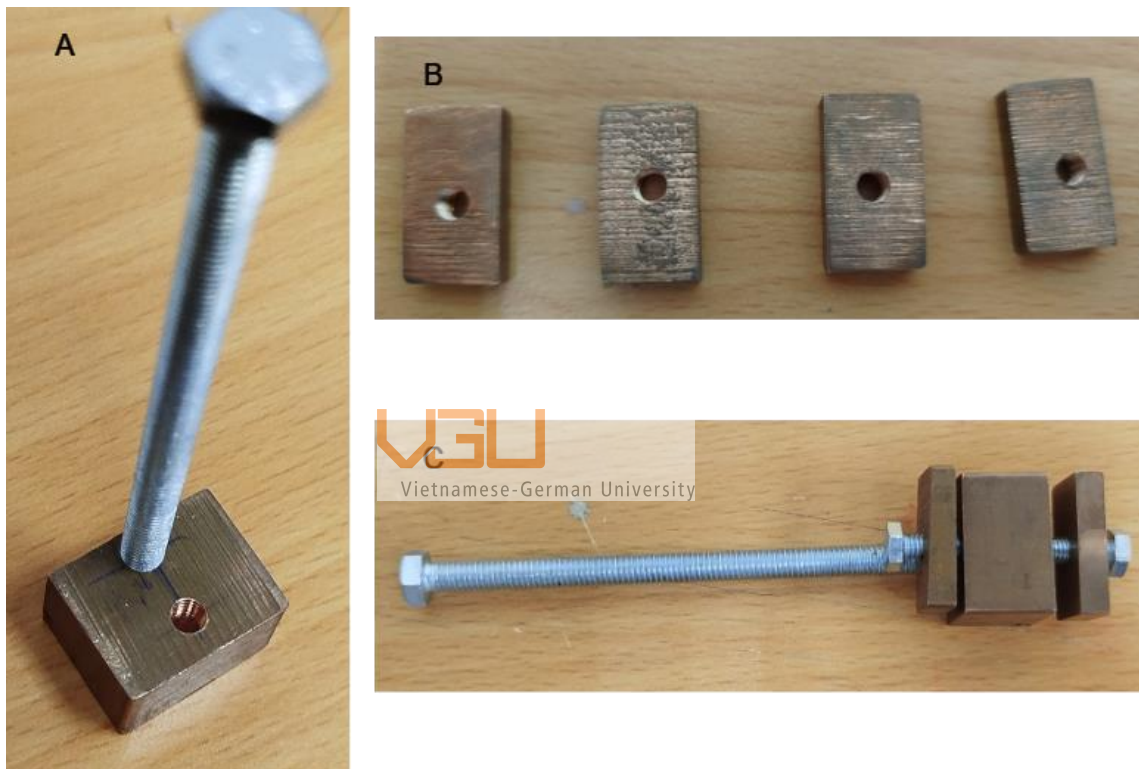


Figure 1: Current collector. (A) current collector's body; (B) security cap; (C) current collector assembly.

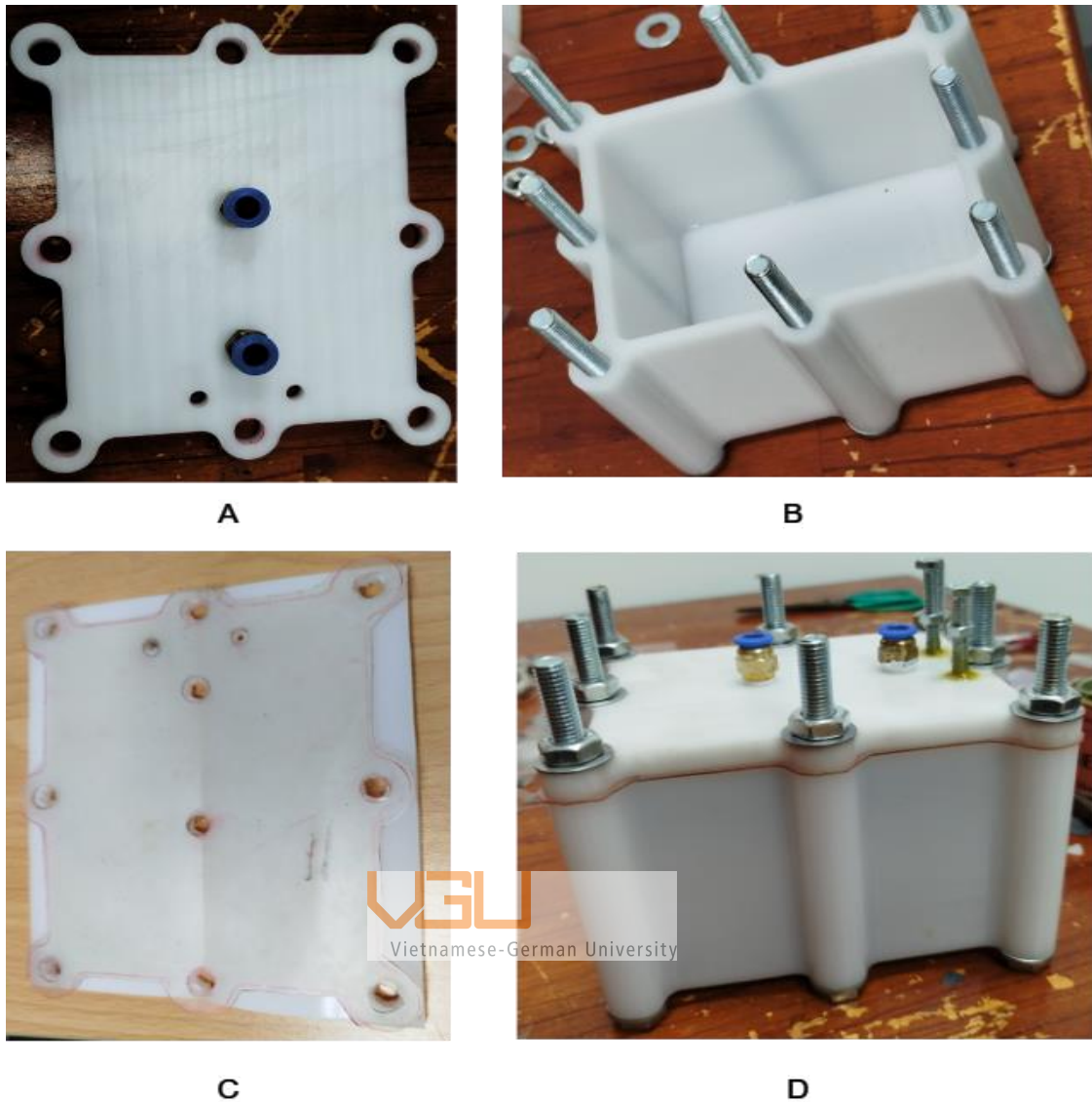


Figure 1: CDI cell. (A) top mount; (B) body; (C) anti-leakage measure (made of silicon sheets); and (D) CDI cell assembly.

Integration of monitoring system

The monitoring system is comprised of a micro-controller, various sensors, and a liquid crystal display (LCD). The sensors are responsible for measuring the quality parameters of water and transmitting this data to the micro-controller, which in this case is the Arduino Mega 2560. Within the Arduino, the incoming signals are analyzed through programming logic, allowing the system to detect any deviations from the safe range of values. In the event of such anomalies, the Arduino can not only issue warnings but also take control actions to rectify the situation; these notifications and potential issues are then displayed on a 20 by 4 LCD screen, as depicted in the accompanying figure.

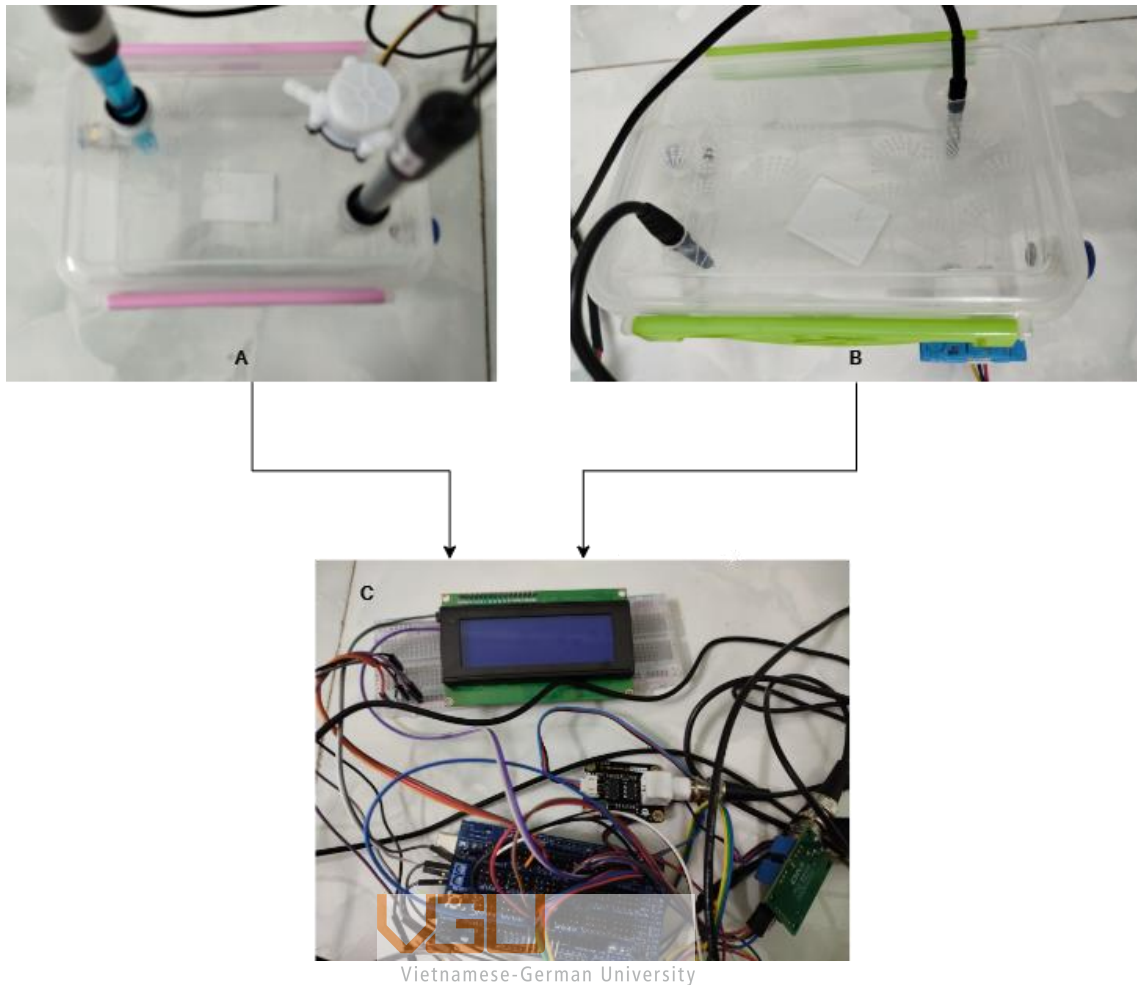


Figure 2: Monitoring system with (A) input sensors station, (B) output sensor station, and (C) Arduino with 20x4 LCD.

C. Experimentation

Feed water characterization (conductivity, pH, etc.) based on Vietnamese brackish water affected by saline intrusion

In the introduction of this thesis, the discussion on the saline intrusion context in Vietnam, particularly in the Mekong Delta region, sheds light on the importance of the salt line thresholds of 1g/L and 4g/L in relation to the distinctive characteristics of brackish water in Vietnam. The primary goal of the project is to address the freshwater requirements of households for fulfilling essential daily activities such as drinking, cooking, and other sanitation needs. To achieve this objective, a series of experiments were carried out to replicate water conditions with total dissolved solids (TDS) levels below 1000ppm, ranging from 100ppm to 600ppm. Brackish water, as defined in this study, encompasses water samples with TDS measurements falling between 500ppm and below 15000ppm,

specifically within the Vietnamese brackish water context. The research conducted within this framework aims to provide valuable insights into the management and utilization of water resources in regions grappling with saline intrusion issues, such as the Mekong Delta in Vietnam. It also seeks to offer practical solutions for ensuring adequate freshwater access for domestic purposes in areas where brackish water prevails, thereby enhancing the overall quality of life for residents.

System operation under various conditions (flow rates, voltage)

The system has been meticulously crafted to possess the ability to function effectively under a diverse array of operational circumstances, encompassing variables like flow rate and operational voltages. Anticipations are in place for the desalination setup to generate no less than 1 liter of treated water each minute, although this output can be further augmented. However, in order to safeguard the desalination process's efficiency, it is imperative that the effluent is afforded sufficient time to interact between the electrodes. To streamline the process and mitigate the necessity for a programmable pump during testing phases, the system adopts a diaphragm pump sourced from China, noted for its low energy consumption, thus ensuring that the system satisfies the minimum flow rate prerequisites. The power supply for the CDI cell utilizes a buck converter equipped with switches to alter the output voltage within the range of 0.8V to 2.5V. However, to prevent undesired side reactions, particularly Faraday reactions that may occur and gain importance when the supply voltage exceeds 1.5V, the system will opt for a voltage level that is below the threshold of 1.5 volts. By implementing this strategy, the system aims to mitigate the risks associated with elevated voltage levels and ensure the smooth operation of the CDI cell without compromising its performance or longevity.

Water quality monitoring throughout the process (conductivity, pH, etc.)

For a desalination project, the primary concern lies in the assessment of water quality, with salinity being the pivotal parameter of interest. Salinity is commonly quantified in various units such as grams per liter (g/L), parts per million (ppm), or in terms of electrical conductivity (measured in microSiemens per centimeter). In the context of this particular project, the monitoring of water salinity is facilitated through the deployment of electrical conductivity sensors, enabling the measurement of salinity in parts per million (ppm), a prevalent unit of analysis in the realm of water treatment facilities. The pH value stands as the second most crucial parameter in the context of a water treatment facility. This

particular value plays a direct role in determining the overall quality of the water being processed. In order to maintain a supply of water that is both safe and suitable for consumption, it becomes imperative to consistently monitor and regulate the pH value. Within the system, there are built-in safety measures that serve to alert operators and halt the treatment process should the pH value deviate from the accepted range, which typically falls between 6 and 8. The primary rationale behind the necessity to suspend operations in such instances is rooted in the absence of any mechanism within the system that can actively adjust the pH level of the water being treated.

Data collection and analysis

The sensors and micro-controller were interlinked with a laptop in order to systematically collect and archive data while conducting various experiments within the research study. Subsequently, the acquired data underwent a series of analytical procedures before being visually represented through graphical illustrations, which will be extensively examined and scrutinized in the forthcoming sections of the thesis dedicated to results and discussions. The visualization of data through graphs serves as a pivotal component in comprehending and interpreting the outcomes of the experiments, providing a visual representation that enhances the clarity and understanding of the research findings. Important parameters of the system were gathered and transformed into visual representations, specifically graphs illustrating the relationship between voltage and current over a period of time, as well as the variations in salinity of the produced water over time within the Capacitive Deionization (CDI) system. In addition to these aspects, further analyses were conducted on other components of the desalination setup, including pre-treatment methods and Ultrafiltration (UF) processes, with the aim of obtaining a comprehensive insight into the mechanisms through which these elements contribute to enhancing the overall desalination efficiency of the CDI unit. This in-depth inquiry provided a detailed scrutiny of the interrelationships between diverse system components, highlighting the potential synergies that could be employed to optimize the desalination effectiveness of the CDI system.

IV. Results and Discussion

A. System performance evaluation

In the desalination system, there are three main components responsible for processing the water. Initially, the source water undergoes treatment in three separate cartridges as part of the pre-treatment process. These cartridges consist of an AC cartridge, followed by 10 microns microfiltration, and finally 5 microns microfiltration. Subsequently, the treated water moves on to the ultrafiltration stage where it passes through a UF membrane with a pore size of 0.01 microns. Lastly, the water enters the CDI unit, where it experiences two distinct phases: absorption (charge) and desorption (discharge), completing the purification process.

Firstly, when considering the pre-treatment procedure of the initial three cartridges, varying salinity levels of water were introduced into these cartridges in order to examine the potential impacts of activated carbon (AC) and microfiltration on simulated saline water, predominantly characterized by the presence of sodium ions (Na^+) and chloride ions (Cl^-). This investigation aimed to evaluate the efficacy of these treatment methods in addressing the unique challenges posed by saline water compositions. The experiment was conducted in batch mode, where each batch consisted of 50mL of source water containing a small quantity of dissolved salt, to investigate the effects of varying salt concentrations on the resulting outcomes as shown in Figure below. Evidently, the impact of these three cartridges on freshwater with low salt ion content is not significant. Nevertheless, as the salinity of the source water rises to 550ppm, the efficiency of the produced water in eliminating a portion of the salt ions becomes noticeable. This indicates that the performance of the cartridges in reducing salt ion concentration is influenced by the salinity level of the source water. After numerous experimental trials, it can be elucidated that the pre-treatment cartridges gradually accumulated fouling on their permeable surface, resulting in the formation of a layer that had the potential to entrap certain salt ions present in a moderately saline water sample, as illustrated in Figure. This phenomenon may be attributed to the prolonged exposure of the cartridges to the saline water, leading to the buildup of fouling material which could act as a barrier for the salt ions, hindering their passage through the cartridge.

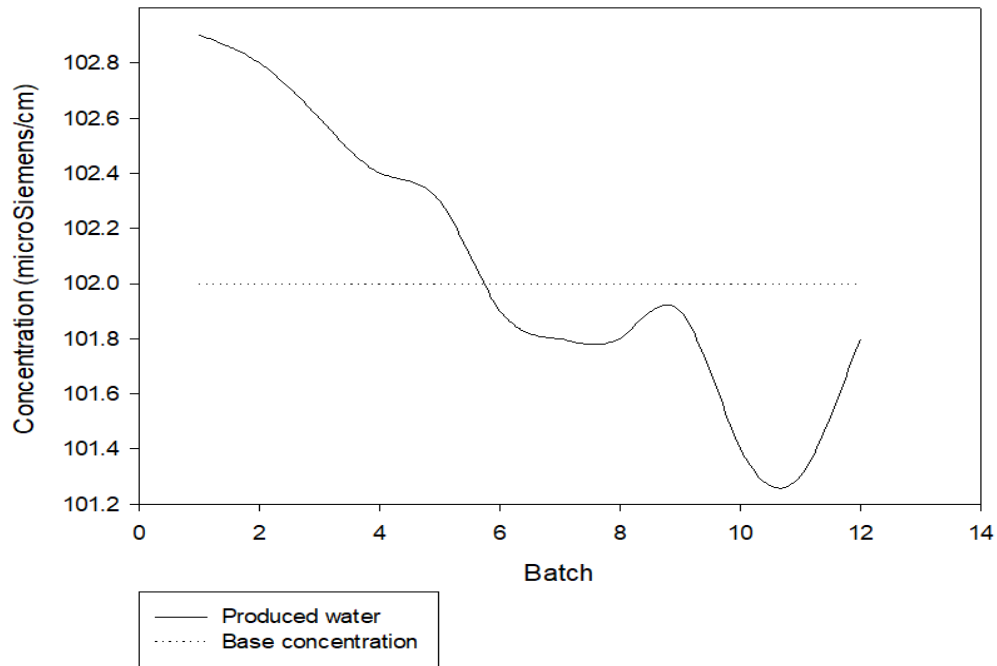


Figure 1: Batch mode testing of three pre-treatment cartridges with low salinity water.

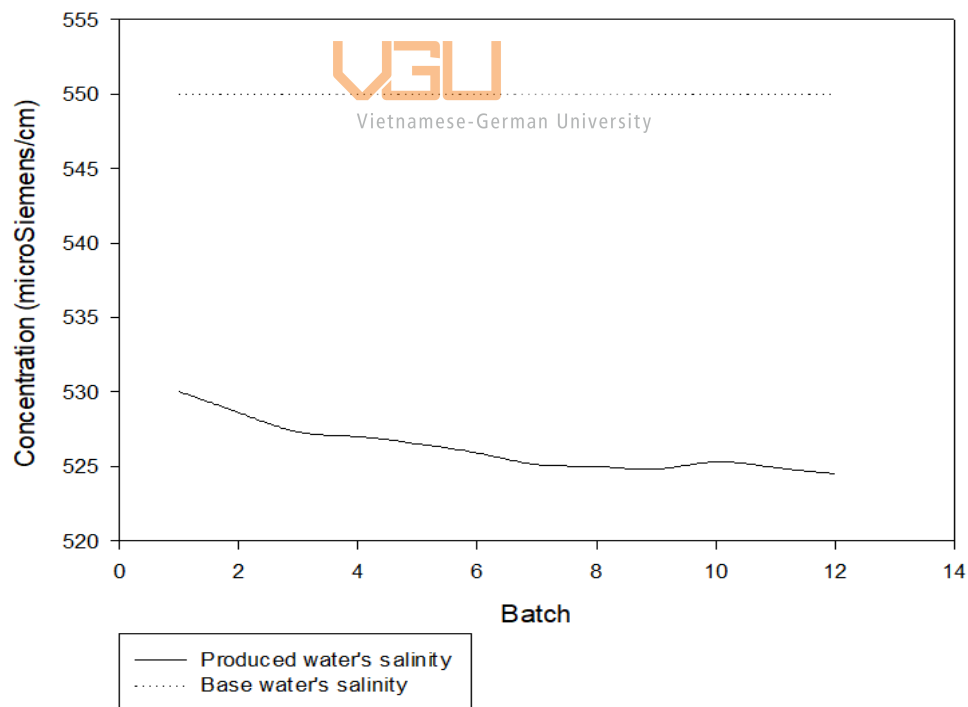


Figure 1: Result of batch mode testing of pre-treatment cartridges in removing salt ions in moderate salted water.

Experiments were conducted to explore the potential of ultrafiltration (UF) in enhancing the desalination process, following a methodology similar to that employed for the initial

three cartridges. Samples of produced water, each containing 50mL, were gathered and subjected to salinity measurements. Initially, the UF cartridge was assessed in isolation using low-saline water with a conductivity of 108.5 microSiemens/cm. The findings indicated limited effectiveness in reducing the salinity of the feed water, as illustrated in the accompanying figure.

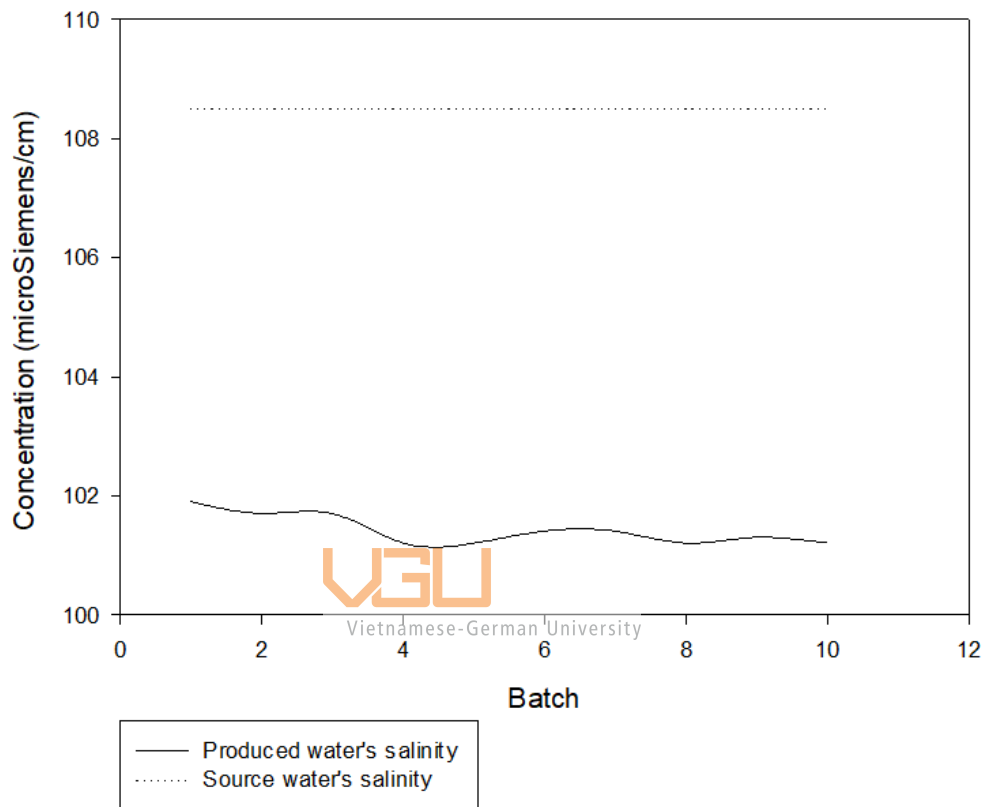


Figure 1: Illustration of batch mode testing of low salinity water after going through UF membrane.

When the salinity is elevated and the initial three pre-treatment cartridges are utilized in conjunction with the UF cartridge, the consistency in the concentrations becomes disrupted, resulting in a remarkable efficacy in salt ion elimination in the initial batches, which subsequently diminishes gradually until a consistent level is reached, as illustrated in Figure.

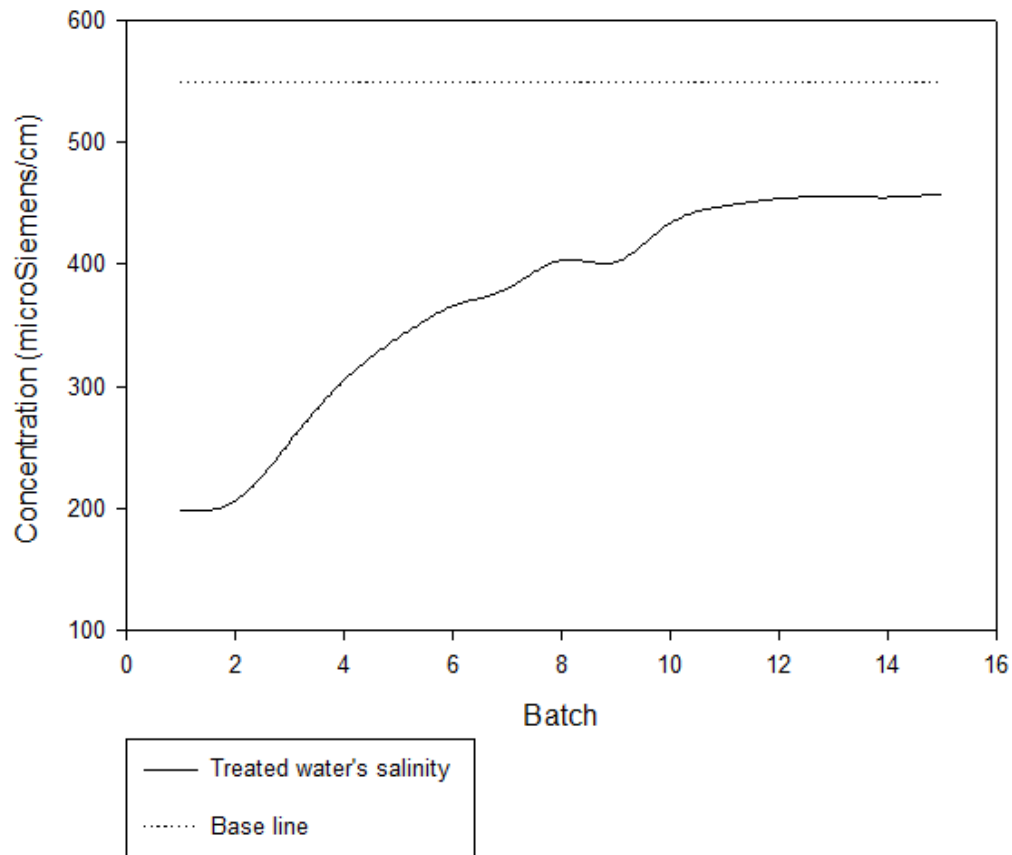


Figure 1: Combined Pre-treatment cartridges with UF membrane test results in batch mode.

The experiment was carried out using a batch mode system, with each batch consisting of 50mL of water. Initially, there was a notable improvement in the removal of salt ions; however, this effectiveness decreased considerably after approximately 500mL of produced water had been collected. While this observation has the potential to contribute to advancements in desalination techniques, the overall performance is insufficient for long-term application. Although the effectiveness of UF membrane technology in eliminating solvent ions from water has been reported to have minimal impact in various scientific publications, the integration of UF with other innovative technologies could present a promising opportunity for enhancing the overall performance of this technology within the context of desalination processes.

Before delving into the investigation of the CDI cell unit, with its multiple pairs of electrodes, an initial examination was conducted on a single pair of electrodes. This preliminary step aids in the prediction of the CDI cell's overall performance and contributes to a deeper comprehension of how the effluent is impacted by the processes

of electro-adsorption and desorption. Moreover, this analysis provides valuable insights into the performance of a single pair of electrodes in removing salt ions through the calculation of salt absorption rate (SAC) and average salt absorption rate (ASAR). The experimental subjects consisted of pairs of electrodes measuring 5cm by 5cm, which were placed within a laboratory cell for conducting single pair tests. A comprehensive measurement process was initiated to determine the quantity of the various working materials present, such as activated carbon and other chemical additives, in addition to the weight of the graphite sheet that bore the responsibility for electrical conductivity.

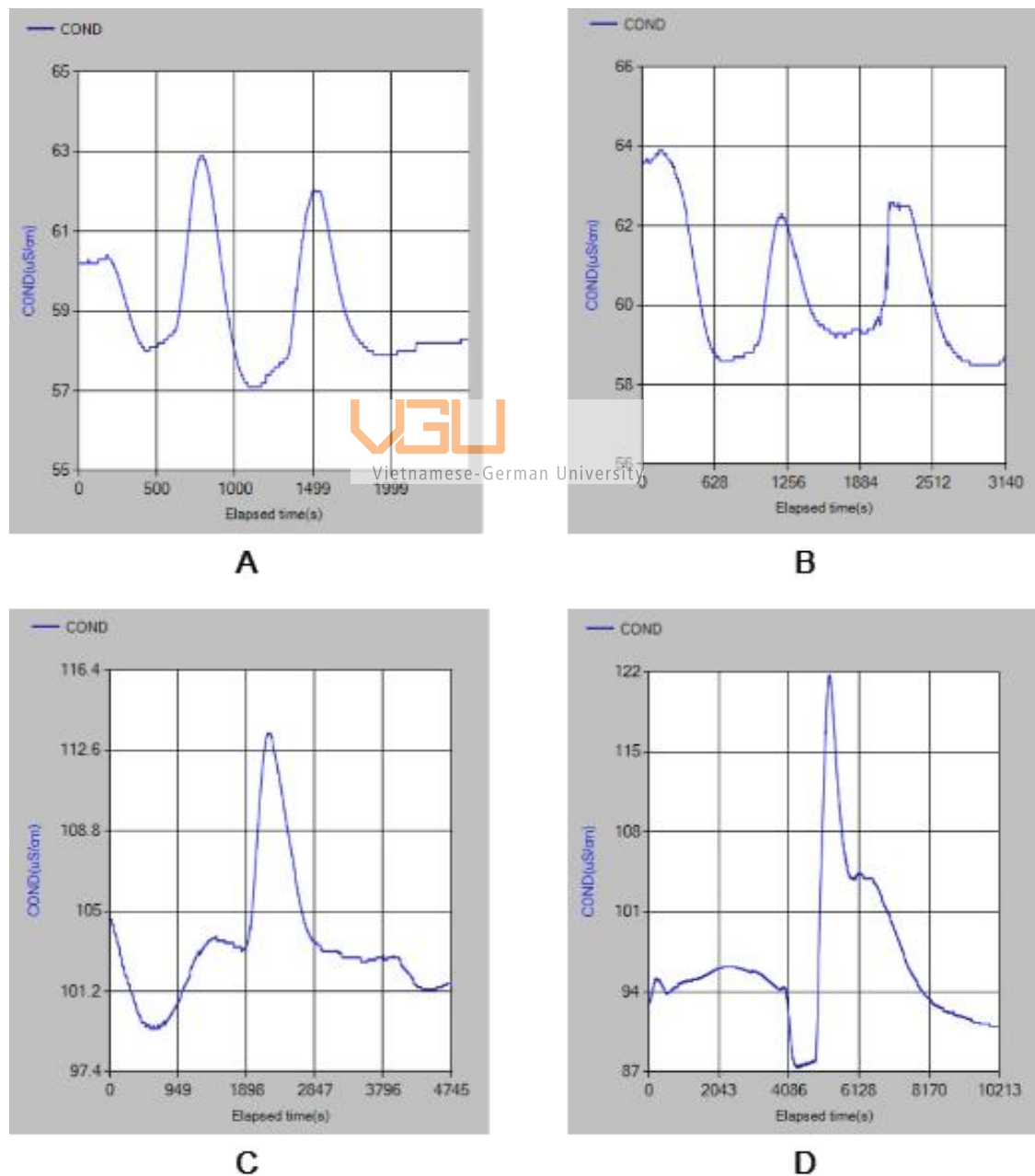


Figure 2: Test result of single pair of electrodes from Siontech with various of salinity.

The weight of the electrode material, excluding the graphite sheet, is calculated to be 0.034 grams based on an electrode area of 1 square centimeter. When considering the dimensions of the electrode to be 5cm by 5cm, the combined weight of the activated carbon (AC) and additives in a pair is determined to be 1.7 grams. With a flowrate of 20mL per minute, it can be determined that the SAC from the C result (which is considered the most stable and suitable for calculation purposes as depicted in the Figure) would equate to 70.59 mg/g. From the SAC, the ASAR can be determined using the mathematical expression outlined in the relevant academic sources. As the duration for absorption time approaches 1500 seconds, the calculated value for ASAR is 0.047 mg/s.

The CDI cell unit underwent experimental investigation to assess its effectiveness in different modes of charging and discharging (reverse voltage discharge) periods, as well as with slight variations in the salinity levels of the feed water. In this experimental setup, the CDI cell has the capacity to accommodate a maximum of 50 pairs of electrodes, each measuring 10cm by 10cm.

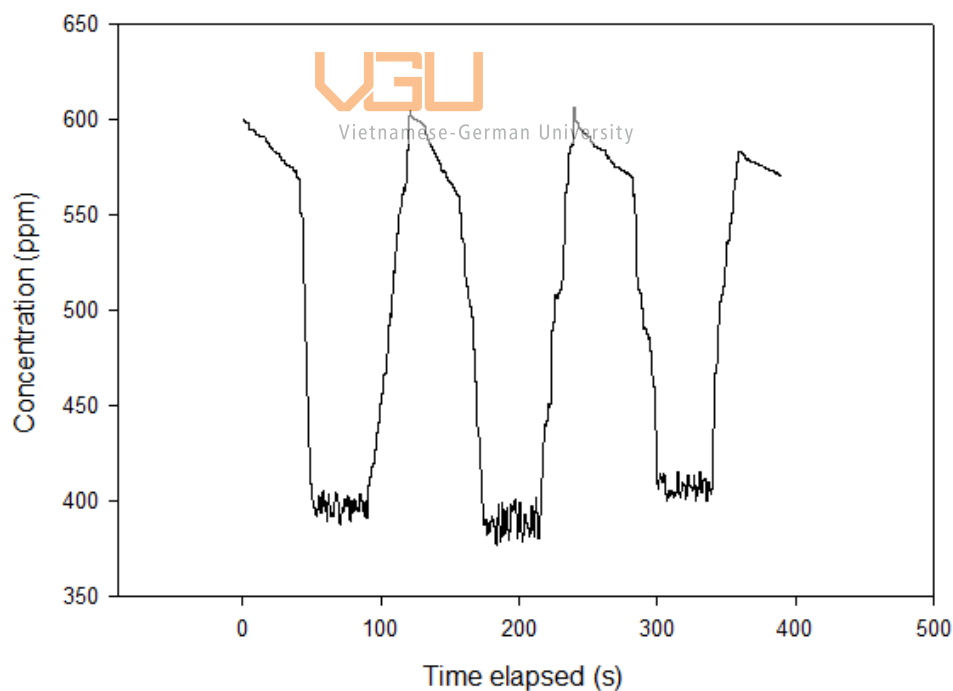


Figure 2: CDI cell unit performance with 500ppm feed water, 120 seconds duty cycle with 100 seconds charging and 20 seconds discharge.

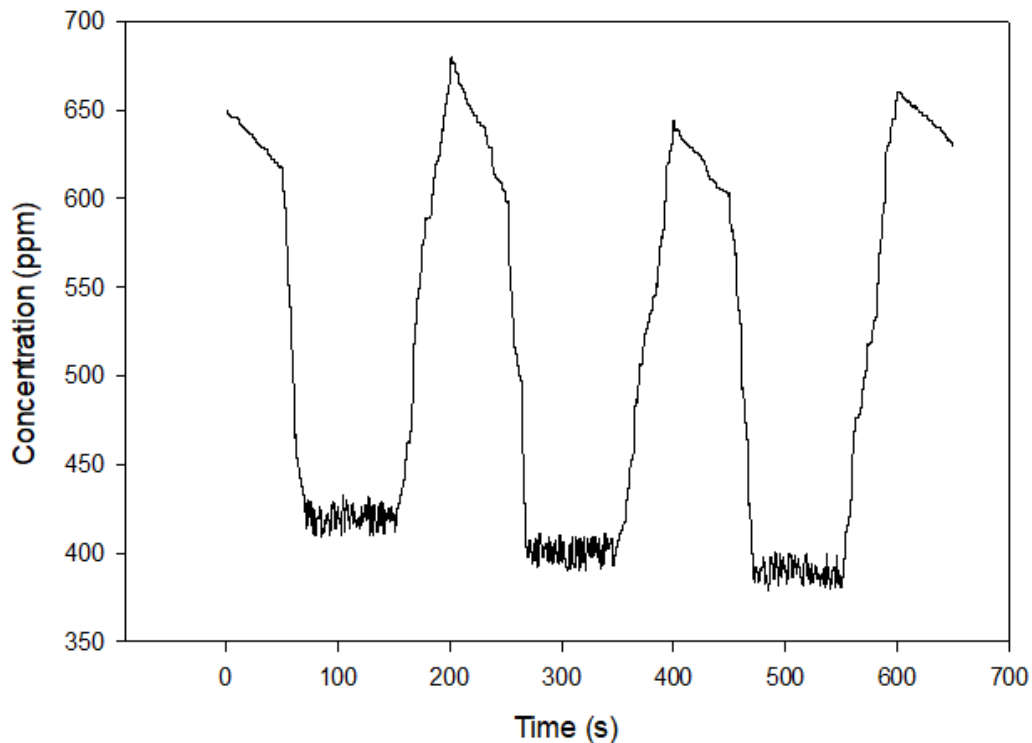


Figure 2: CDI cell unit with 200 seconds cycle (150s charging and 50s discharge) with feed water salinity is 550ppm.

The stability of electrodes is significantly enhanced when they are arranged in multiple pairs, demonstrating remarkable durability by maintaining consistent values of SAC and ASAR over an extended duration without degradation. The extended duty cycle results in a marginal enhancement for the CDI cell, even with the rise in salinity of the feed water; the peak of the absorption phase continues to achieve levels around 400ppm. This phenomenon suggests that the CDI cell's performance is only minimally affected by variations in the duty cycle, indicating a robust capability to maintain efficient ion removal even under changing feed water conditions.

Finally, an examination is conducted on the overall efficacy of the desalination system, wherein efforts are made to streamline processes, leading to the gathering of data during the absorption phase through batch mode testing, with each individual batch having a volume of one liter. The system's resilience and performance in saline water show a noticeable improvement only after the production of 2 liters of freshwater, a phenomenon that can be attributed to the decreased efficiency of the membranes and the CDI's electrodes as a result of incomplete desorption phases. This observation suggests a potential correlation between the quality of the produced water and the operational status of the membrane and electrodes in the system.

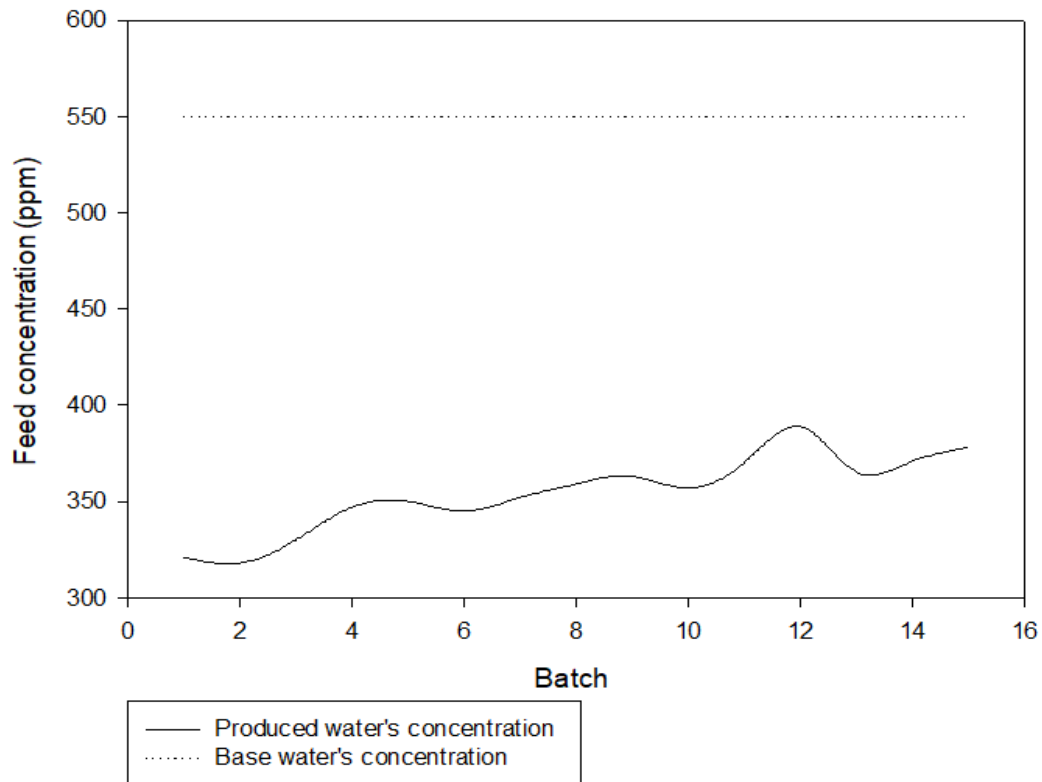


Figure 2: Desalination system performance against 550ppm feed water in batch mode.

B. Effectiveness of water quality monitoring

The incorporation of an extensive array of sensors and micro-controllers within a desalination facility serves to optimize its operations and provide valuable insights into the performance of the overall system. This integration not only enhances efficiency but also simplifies the process of data collection for future research endeavors. Moreover, the monitoring system is equipped to alert the operator or user through LCD display messages in instances where the water quality is deemed unsatisfactory or in scenarios requiring system shutdown, such as when the water acidity levels are too high for safe usage, when the pretreatment system necessitates cleaning due to fouling, or when the pump malfunctions. The monitoring system has been designed with an interactive interface to allow users to easily check the status of both input water sensor stations and output sensor stations. By simply pressing a button, users can switch between the three main displays available. The first display provides information on the input water station, housing high-range electrical conductivity sensors, flowrate sensors, and pH sensors. Moving to the second display, users can see the status of the output water sensor station, which includes temperature sensors, turbidity sensors, and low-range electrical conductivity sensors.

Pressing the button once more will lead the user to the third display, where any potential problems can be quickly identified with a single glance.



Figure 2: Monitoring system; (A) First displays shows input sensors status, (B) second displays shows output sensors status and (C) error displays in Vietnamese language.

The parameters set for issuing warnings are outlined as follows: in cases where the pH value falls outside the optimal range of 6 to 8, the system is programmed to issue a warning regarding the pH value and automatically halt its operations in order to prevent any harm to the sensitive desalination system. Furthermore, should the output Electrical Conductivity (EC) value surpass the threshold of 300ppm, the system will promptly generate a salinity warning alert. Moreover, if the turbidity value deviates from the specified range, the system will prompt the operator to inspect the pre-treatment cartridge and carry out a washing procedure as necessary. Additionally, in situations where the

flowrate sensor fails to detect any water inflow into the system, the system will come to a halt and provide instructions for the operator to examine the pump or investigate potential clogging issues.

C. Discussion of challenges and limitations

Membrane fouling and cleaning procedures

The current project employs multiple membranes as pre-treatment strategies before introducing water into the Capacitive Deionization (CDI) unit. It is widely acknowledged in the literature that membranes are susceptible to fouling, a challenge that has been extensively discussed in the literature review conducted for this project. When it comes to addressing fouling in these membranes, there are two primary options available. The first method involves chemical cleaning, while the second option is backwashing. Chemical cleaning is deemed unsuitable for the current system due to the CDI desalination system's emphasis on minimizing chemical usage, thereby enhancing its eco-friendliness. Conversely, backwashing emerges as a more viable alternative, given its cost-effectiveness since it eliminates the need for chemical cleaning agents. Furthermore, the pre-treatment system selected for this project is specifically tailored for backwashing procedures. It is generally recommended that membranes, particularly those used in microfiltration (MF) and ultrafiltration (UF), undergo backwashing at least once a week in commercial settings. To initiate the backwashing process, one simply needs to disconnect the feed tube from the output port of the membrane cartridges and proceed with the backwashing procedure. This routine maintenance step plays a crucial role in reducing fouling, thereby promoting the longevity of the membranes and optimizing the overall desalination performance of the entire system.

Optimization of process parameters for improved performance

Some enhancements may be implemented to the operational parameters, such as elevating the voltage supply to the CDI unit; theoretically, the ideal voltage for CDI operation is 1.5 volts. Nevertheless, in practical scenarios, particularly during experimental trials, a substantial portion of the voltage is dissipated due to voltage drop as it traverses through the current collectors and electrodes. Augmenting the voltage through the utilization of a buck converter to 2 volts could potentially yield favorable outcomes in terms of enhancing the desalination efficacy of the CDI unit. Furthermore, this adjustment could lead to improved overall performance and efficiency of the

desalination process conducted by the CDI unit but still insignificant for Faradaic reactions to happen on the electrode's surface. Another proposed optimization strategy involves altering the flowrate, a recommendation highlighted in the existing literature, as ASAR is a crucial parameter in the context of CDI process. When the flowrate is adjusted to a slower rate, there is a potential for enhancing the desalination system by allowing more time for water to reside within the CDI unit, consequently facilitating the achievement of maximum SAC.



V. Conclusion

The primary objective of this dissertation is centered around the development of a desalination system that incorporates the combination of ultrafiltration (UF) and capacitive deionization (CDI), along with an integrated automatic operation and monitoring system, to enhance the overall desalination process. The primary goal of this research endeavor is to address the pressing issue of saline intrusion, which poses an increasingly severe threat to the populace of Vietnam, particularly in the Mekong Delta region. The system being developed is at a pilot scale, designed to cater to household needs, with a projected capacity exceeding 1 cubic meter per day and an input flowrate of 1 L/min. Through its operations, the system has demonstrated the capability to reduce the salinity of incoming water from 550ppm to approximately 350ppm, resulting in a difference of 200ppm and rendering the water safer for consumption and various other applications. Experimental observations have indicated that both microfiltration (MF) and ultrafiltration (UF) play a significant role in the desalination process, contributing to the reduction of salinity levels, despite existing literature suggesting that MF and UF may not be highly effective in the removal of salt ions. This observed phenomenon could potentially be attributed to the accumulation of salt ions within fouling layers on the membranes, leading to an overall decrease in salinity levels.

The incorporation of automation and monitoring systems plays a crucial role in enhancing the efficiency and effectiveness of desalination systems. By automating processes such as charge and discharge through reverse voltage discharge (RVD), the value of the system is significantly increased. Additionally, the integration of a monitoring system featuring an interactive user interface allows users to gain a comprehensive understanding of the system's status with just a quick glance, thereby facilitating informed decision-making and operational control. This technological advancement not only streamlines maintenance procedures for these intricate systems but also elevates overall performance levels to meet evolving demands in the field of desalination.

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