

Article

Circular Economy Framework for Energy Recovery in Phytoremediation of Domestic Wastewater

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Abstract: Circular economy (CE) strategy is crucial in developing towards sustainable growth. It was created to promote resource utilization and the elimination of waste production. This article aimed to study the possibilities of using the CE framework in wastewater bioremediation and energy recovery using hydroponic tanks. The integration of phytoremediation with bioenergy, construction and lifespan of hydroponic tanks in phytoremediation of wastewater, selection of aquatic plants and the expected challenges in the implementation of CE in phytoremediation of wastewater were discussed. The plant-based biomass harvested and the relative growth rate (RGR) of the selected plants from the phytoremediation process was evaluated. The findings obtained indicated that the selected plants tripled in weight after 14 days cultivation period at different retention times. *E. crassipes* recorded the highest growth with $2.5 \pm 0.03 \text{ g g}^{-1} \text{ d}^{-1}$, followed by *S. molesta* with $1.33 \pm 0.05 \text{ g g}^{-1} \text{ d}^{-1}$ and then *P. stratiotes* recorded $0.92 \pm 0.27 \text{ g g}^{-1} \text{ d}^{-1}$ at the end of the cultivation period. Therefore, the selected plants have been identified as having the potential to be used in phytoremediation as well as a source of energy production. The outcome of our review suggested the adoption of a lifecycle assessment as the CE framework for the phytoremediation of wastewater.

Keywords: bioenergy; circular economy (CE); phytoremediation techniques; relative growth rate (RGR); plant-based biomass; wastewater treatment



Citation: Mustafa, H.M.; Hayder, G.; Mustapa, S.I. Circular Economy Framework for Energy Recovery in Phytoremediation of Domestic Wastewater. *Energies* **2022**, *15*, 3075. <https://doi.org/10.3390/en15093075>

Academic Editors: Bamidele Victor Ayodele, Thanikanti Sudhakar Babu and Dino Musmarra

Received: 24 January 2022

Accepted: 10 March 2022

Published: 22 April 2022

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1. Introduction

The circular economy (CE) approach has received a lot of attention from industries, academics and policy [1,2]. Circular flow models, sustainable concepts, as well as lifecycle thinking are all geared towards reducing environmental pollution while simultaneously opening up new commercial prospects through waste recycling, repair and reprocessing [3,4]. The main aim of CE is to eliminate or minimize waste generation [5]. Preventing waste generation and repurposing it has become a novel strategy in economy revitalization. Therefore, systems that allow total or partial circularity of materials have replaced linear waste processes, as their design and operations are necessary and socially mandated [6]. In CE framework, the materials and products remain in the economy and waste is considered as raw materials that can be recycled into new products [7]. This sets it apart from the “take-make-use-dispose” of the linear model, in which waste is typically the final stage of the product lifecycle [8]. CE also emphasizes on economy, environmental and social sustainability of the conventional economic system [9]. On the contrary, the linear

model cannot be used in demonstrating the natural and social implications on the economy, as they are not oriented around minimizing the harmful elements in industrial systems. Therefore, CE is a component of the conventional economic system that emphasizes circularity in energy and materials in conjunction with natural resource conservation [10]. For instance, the European Union has found that the utilization of waste as raw materials by industries is important, as proven by a Dutch-based plant that successfully converted raw materials and energy to biomass, phosphate, copolymers and bioplastics. This novel technique has the potential to boost alternative business models based on CE [11].

Moreover, the CE approach could pave the way for new inventions in hydrology that would aid in water restoration. Water has been a topic of contention in CE because it is one of the most critical resources for industrial activities. Agriculture and aquaculture, for example, are entirely reliant on it [12]. Additionally, incorporating energy production and resource recovery into clean water production and wastewater treatment is now part of the CE concept [13]. In this way, wastewater treatment and reuse can help increase agricultural productivity, provide new materials for industrial applications, or create new energy sources like methane and biofuels [12].

Furthermore, water, raw materials and energy are the three main pathways for CE in wastewater, and they are all supported by innovation [14]. The principle of reducing, reusing, recycling, recovery and restoring supports the link between waste-to-energy [15]. Energy consumption for wastewater treatment operations varies based on the process configurations, the treatment goals and effluent standards. Energy usage is often less than 0.5 kW h/m³ for operations that do not include nutrient removal. Advanced treatment such as activated carbon filtration and membrane filtration are usually used in WWTPs for eliminating excess nutrient, pathogens and other contaminants present in wastewater. These procedures consume a significant amount of energy, ranging between 0.5 to 2.0 kW h/m³ [16]. Nevertheless, biological methods of wastewater treatment such as phytoremediation can help reduce dependency on fossil fuel energy sources while increasing reliance on renewable energy sources, which can help reduce carbon emissions.

Recent studies have demonstrated that macrophytes (aquatic plants) can remove both inorganic and organic pollutants from wastewater [17]. Phytoremediation utilizes the plant roots in absorbing or degrading excess nutrients in wastewater. Phytoremediation is a cheap and sustainable technique of wastewater treatment that can be employed in hydroponic or built wetlands systems [17]. Emergent, submerged and floating aquatic plants can be used in phytoremediation of wastewater [18]. Furthermore, the ability of these plants to remove contaminants and absorb nutrients differs depending on the origin and properties of the wastewater used in the research [19]. Thus, the purpose of this article was to outline new CE approaches in wastewater treatment in order to integrate and develop a suitable CE framework for simultaneous phytoremediation of wastewater and bioenergy generation. Furthermore, creating a comprehensive circularity assessment methodology is essential to enable and support a strategic CE framework for phytoremediation techniques in wastewater treatment. A complete view of the feedstock conversion process into valuable end products should be included in the CE strategy. Therefore, the CE framework was proposed for the reuse of biomass harvested from the phytoremediation of domestic wastewater.

1.1. Integration of Phytoremediation with Bioenergy Production

One of the most effective approaches for the management of biomass from polluted sites is combining phytoremediation with bioenergy production, which is becoming increasingly popular. Zhao et al. [20], for example, discovered that plant biomass could fulfill a substantial amount of the world's energy needs. Hence, utilization of energy crops for phytoremediation can assist in meeting energy demands while also reducing greenhouse gas emissions by using a sustainable, environmentally benign and carbon-neutral biomass source. A variety of well-known crops have been recognized as having the potential to be utilized in the phytoremediation process as well as being a source of

energy production. The integration of phytoremediation and bioenergy production using a single hemp crop has been reported to be a potential pathway to overcoming the economic limitations of phytoremediation schemes. Rhey et al. [21] investigated the potential of paired phytoremediation and bioenergy production using hemp crop (*Cannabis sativa* L.). The outcome of the study indicated that hemp growth has been successfully proved at the field scale for phytoremediation and in key bioenergy conversion technologies. Additionally, Osman et al. [22] investigated the potential of employing *Pennisetum purpureum* for phytoremediation and bioenergy production. The study revealed that *P. purpureum* contains high levels of lignocellulosic content, which can be used as a carbon source for the production of bioenergy like ethanol and butanol. This concept is in line with the CE concept (zero-waste idea) of combining phytoremediation and bioenergy.

1.2. Organization of the Paper

There are several aspects to this article. The first section described the context of CE in wastewater treatment and integration of phytoremediation with bioenergy production. The materials and methods are described in the second section, while the third section presents the research findings. The fourth section presents the expected problems and opportunities in applying CE strategies in phytoremediation techniques, as well as the prospects of CE in phytoremediation of wastewater. The last section of the study concludes with observations based on the analysis and outcomes of the related publications selected for the review.

2. Materials and Methods

2.1. Review Methodology

The literature search was performed on Scopus and Google Scholar search engine using the title “circular economy”, “circular economy study for wastewater treatment” and “circular economy for phytoremediation of domestic wastewater”. The search yielded a collection of academic publications. The literature screening was conducted by perusing the abstracts, methodologies and conclusion sections. More than 50 documents were used for the study. This study was confined to CE techniques in wastewater treatment published from 2017 to 2021. However, to fully grasp the potentials of phytoremediation techniques in wastewater treatment, it is necessary to understand the mechanisms of the phytoremediation techniques in wastewater treatment, selection and cultivation of the aquatic plants and conversion of the waste (biomass) generated from the phytoremediation process into valuable new products.

2.2. Construction of Hydroponic Tanks

This present research was conducted from 2019 to 2021. Four hydroponic tanks were constructed for the phytoremediation of domestic wastewater. At the initial stage, a literature review was conducted to gain insights on the materials, design methods and the dimension of the hydroponic tanks suitable for the cultivation of different aquatic plant species in order to achieve the desired outcome. Additionally, transparent acrylic glass was used to construct the hydroponic tanks to allow physical observations of the changes and interactions between the root of the plants and the settleable particles in the wastewater treatment system.

2.3. Selection of the Test Plants

The choice of suitable plants for cultivation in phytoremediation of wastewater is crucial [23]. In most cases, availability, growth rate, temperature, environmental conditions, pH and the cultivation system are often considered when selecting aquatic plants for phytoremediation processes. In this research to select the most appropriate plants, we identified several potentially beneficial aquatic plants that could be used. We identified *Wolffia* (water meal), *Spirodela* (giant duckweed, big duckweed), *Lemna minor* (common duckweed), *Azolla pinnata* (water velvet), *Eichhornia crassipes* (water hyacinth), *Ipomeo aquatic* (water spinach), *Typha domingensis*, *Salvinia molesta* (giant salvinia) and *Ceratophyllum*

demersum. These plants were identified by considering their nutrient uptake capacity, availability, adaptability to adverse climate, ability to withstand the concentration of the contaminants present in the wastewater, biomass yield, ease of management and resistance to pests. The results obtained from the selection process are presented in the Results and Discussion section.

2.4. Harvested Biomass from Phytoremediation of Domestic Wastewater

The application of phytoremediation techniques in wastewater treatment involves the selection of suitable aquatic plants, nutrient uptake and the beneficial use of the harvested plant biomass [24]. Otherwise, the disposal of the harvested plant biomass might lead to the release of the stored nutrients into the environment [25].

2.5. Relative Plant Growth Rate (RGR) of the Selected Plants at Different Retention Times

RGR is a parameter used in measuring the changes observed in the growth rate of cultured plants while utilizing nitrogen and phosphates [19]. The RGR was evaluated using Equation (1) [26], and expressed in $\text{g g}^{-1} \text{d}^{-1}$. The densities of the *E. crassipes*, *P. stratiotes* and *S. molesta* plants were measured using a weighing balance. Additionally, the summary of the data collection and methodology is described in Table 1.

$$\text{RGR} = \frac{\ln Q_2 - \ln Q_1}{T_2 - T_1} \quad (1)$$

Q_1 and Q_2 are the initial and final density of the fresh plants. T_1 and T_2 represent the time.

Table 1. Summary of data collection and methodology.

Scenario 1	80 g of the three selected plants (<i>E. crassipes</i> , <i>P. stratiotes</i> and <i>S. molesta</i>) were separately cultivated in the hydroponic tanks containing the domestic wastewater.
Scenario 2	The treated and untreated water samples were collected at 2-day intervals at different retention times.
Scenario 3	Harvesting of the plants (biomass) was carried out every 7 days.
Scenario 4	The RGR was calculated at different stages of 6, 12 and 24 h retention times.

3. Results and Discussion

This section describes the outcomes of the literature search, construction of the hydroponic tanks, selection of the test plants, plant biomass harvesting and the RGR calculated for each of the cultivated selected aquatic plants at different retention times of 6, 12 and 24 h.

3.1. Outcome of the Review

The papers selected for the review were major academic papers that included research, review articles and reports from industries. We observed that most CE literature was based on case studies from surveys. Few theoretical works described the conceptual frameworks and taxonomies of circularity measurements at different levels of development in different countries, as well as the reuse and recycling efficiencies. According to our literature survey, we found that there was a lot of interest in providing industries with different tools and strategies that would facilitate the use of efficient production and environmental management practices. Nevertheless, no available general indicators can simultaneously assess the ecological and productivity efficiencies [27]. As a result, measures for waste reduction and promotion of CE practices in industries are becoming more extensively embraced. Notwithstanding, there are several difficulties associated with analyzing CE, because no single indicator of circularity can capture all the characteristics [5,28].

On this note, recent study has shown that the CE concept have been applied in the evaluation of wastewater treatment for the generation of energy. Flores et al. [12] studied the WWTP policy using the CE framework at the Presa Guadalupe sub-basin. In the study, data were obtained through semi-structured interviews from the stakeholders of the Presa Guadalupe Commission. It was concluded that WWTP policy is of significant importance in the CE model and CE can help improve water quality by contributing to water innovations. Additionally, Hagenvoort et al. [11] employed the CE concept to evaluate the agronomical, social implications and technological reuse of treated wastewater from WWTP. Quantitative and qualitative methods were used in generating the research data. The outcome indicated that there are clear benefits for both farmers and WWTP operators. Besides, Mustapa et al. [29] applied the CE framework in comparing the lifecycle cost of treating sewage sludge for energy generation using anaerobic digestion. The objective of the research was to gain understanding of the potential benefits or implications of environmental and economic impacts related to sludge waste treatment for energy recovery and to serve as a springboard for future study on sludge waste utilization in Malaysia. The outcome of the study confirmed that converting sludge waste into biofuel has significant energy production potential. Likewise, Czikkely et al. [30] used the CE concept in evaluating the material flows in wastewater treatment using mushroom compost. The outcome of the economic analysis showed that mushroom compost could be completely recycled and the difference between $CEV\%_{Sen(mod)} = 87.5\%$ and $CEV\%_{BAU(mod)} = 45.5\%$ was the quantity of primary raw material that was recycled at the end of the lifecycle of the product. Espíndola et al. [31] implemented CE approaches in the recovery of the water cycle via rainwater collection systems in urban areas. The findings of the study revealed that harvesting rainwater could contribute significantly to CE. Additionally, the application of rainwater collecting systems would lead to reduced demand for water. Silveira et al. [32] applied the CE framework in microalgae cultivation at varying retention times in the treatment of swine wastewater. The outcome demonstrated that the study contributed to the reduction of water footprint and long-term viability in the pig farming production chain. Arias et al. [33] implemented the CE approach in improving the sustainability of wastewater from the washing and disinfection of bottles before packaging as a source of water for the cooling process. According to the authors, the wastewater generated due to the washing process is of excellent quality, therefore its reuse in the cooling process is justifiable. The findings revealed that the proposed method was successfully implemented at an industrial scale, resulting in 100 percent water replacement in cooling towers.

Furthermore, Nika et al. [34] developed a game-changing circularity assessment modeling that allowed the analysis of feedback loops between human-managed and nature-managed systems in order to assess the circularity of water and water-related resources. Surinkul et al. [35] used water sampling methods, questionnaires and surveys to measure the material flows and mass for agricultural farms such as prawn, fish and pig farms for the CE concept in wastewater reuse. The study indicated that effluent of wastewater discharged into the environment in terms of total nitrogen (TN) and biological oxygen demand (BOD) loading were the cause of pollution in the farms. In addition, the authors reported that the reuse of 50% of the farm wastewater in agricultural fields as a CE strategy could play a critical role in reducing BOD and TN levels in the environment. Similarly, Saidan et al. [36] conducted a comprehensive analysis of the existing state of wastewater reclamation and reuse in Jordan's major industries highlighting the potential and obstacles of growing wastewater reuse. The authors reported that the study could assist in reducing the cost of reclaimed wastewater reuse. Zvimba et al. [14] reported the implications of adopting waste to energy technologies in CE energy pathway within wastewater treatment. The summary of the previous studies on CE in wastewater treatment is presented in Table 2.

Table 2. Previous studies covering CE in wastewater treatment.

Authors	Area	CE Strategies	Type of Article	Case Study/ Country
Kakwani and Kalbar [37]	Urban water sector		Review	India
Espíndola et al. [31]	Urban rainwater harvesting	Case study/cradle to cradle	Research	Gaudalajara city, Mexico
Somoza-Tornos et al. [38]	Regenerated water	Performance assessment (CE Model design)	Research	Spain
Silveira et al. [32]	Swine wastewater	Case study/lifecycle assessment	Research	Minas Gerais, Brazil
Arias et al. [33]	Wastewater recovery to be reused for in cooling towers	Case study/lifecycle assessment	Research	Spain
Nika et al. [34]	Complex water systems	Developed circularity assessment framework	Research	Fictional city
Kaszycki et al. [39]	Wastewater treatment and waste management	Case study: zero waste path in circular bioeconomy	Research	Poland
Pahunang et al. [40]	Gas emissions from wastewater	Lifecycle assessment	Review	Not mentioned
Surinkul et al. [35]	Wastewater treatment farming	Surveys, questionnaires and water samplings were taken from farms	Research	Thailand
Zvimba et al. [14]	Dry waste sludge	Case study: waste to energy	Research	Not mentioned
Saidan et al. [36]	Reclamation of wastewater	Lifecycle assessment	Research	Jordan
Jedelhauser and Binder [41]	Phosphorous recovery from dry sewage sludge	Spatial analysis based on a triangulation of methods	Research	Germany
Ghimire et al. [16]	Wastewater treatment plants		Mini-Review	USA
Kurniawan et al. [42]	Phytoremediation of wastewater	CE initiatives	Review	Malaysia

Therefore, the findings from the literature survey demonstrated that the CE context can be employed in phytoremediation of domestic wastewater for reuse of wastewater and generation of bioenergy from the harvested plant-based biomass. This technique has the potential to minimize the environmental impact of biomass waste while promoting industrial circularity and viability, hence, contributing to the development of CE within the bioenergy industries. The suggested CE framework is innovative, as it demonstrates feasible methods for implementing the CE concept in the cultivation of aquatic plants for wastewater treatment and biofuels' applications. Thus, the outcome of our review suggests the adoption of lifecycle assessment and water footprint in the CE framework for phytoremediation of wastewater. Furthermore, water footprint and lifecycle assessment have been widely embraced in assessing and improving the environmental impacts of industries [43].

3.2. Lifespan of Hydroponic Tanks in Phytoremediation of Domestic Wastewater

In our short-term research conducted from 2019–2021 on phytoremediation of domestic wastewater using different aquatic plants, we found that aquatic plants are good candidates for nutrient uptake from low-strength wastewater [44]. In the study, we employed a natural

and sustainable technology that does not require energy usage, although, a power source was attached to the submersible pipe and the control timer, which controls the inflow and outflow of the treated and untreated water from the treatment tanks at a fixed time.

Additionally, the hydroponic tanks were changed after three cycles of cultivation due to damage (leakage), wearing out of the adhesive and textural properties of the acrylic material and other actions of the environment. Furthermore, cleaning and preventive maintenance of the tanks were conducted regularly. Each cycle of the 14-day treatment produced a high yield of polished water and plant biomass, where up to 90% reduction efficiency was recorded from the turbidity, color, nitrate, phosphate and ammonia nitrogen analysis performed on the influent and reclaimed water samples. Besides, the practical concept for establishing a long-term industrial scale is yet to be executed. We believe that better improvement in the textural materials used in constructing hydroponic tanks that can last from 6 to 12 months from its installation and start-up would lower the cost of the wastewater treatment processes, while considering proper routine maintenance, selection of appropriate plants to be cultured and nature/type of the wastewater. Comprehensive information on the phytoremediation of domestic wastewater can be accessed online [17–19,44–49]. Therefore, prospects related to optimizing energy, water and nutrient recovery through phytoremediation techniques need to be evaluated on a large-scale or industrial scale across different climatic conditions, as the conversion of harvested aquatic plant biomass into bioenergy or livestock feed would provide stakeholders and entrepreneurs with a possibility to profit from eutrophication. Additionally, resource recovery from wastewater would enable many downstream benefits and ecosystem management. Furthermore, stakeholders must be aware of the full spectrum of remediation alternatives available in order to understand the strategic management approaches available to help provide more rapid environmental gains. Therefore, the application of hydroponic systems for aquatic plants cultivation in WWTPs at industrial scale, as well as optimizing the operational processes, would help in providing insights into the economic, ecological and practical feasibility for commercial enterprises. In addition, analytical evaluations in compliance with recognized standard methods are necessary to up-scale laboratory observations. Moreover, sunlight, wastewater composition, microorganisms and the plant roots are factors that enhance effective and sustainable wastewater treatment and biomass generation in hydroponic systems. Thus, the integration of wastewater in hydroponic systems would promote economic growth and food security for under developed countries [46]. Additionally, pollution, unreliable biomass output and other seasonal environmental changes must be considered and quantified.

Finally, there is considerable opportunity to assess the function of government regulations in line with present environmental management schemes in promoting wastewater remediation [50]. Even though we were unable to determine the total quantity of energy used for powering the submersible pipe and the control timer in our phytoremediation investigations, future research can focus on the amount of energy required or exhausted during the overall phytoremediation of the domestic wastewater in order to shed more light for comparative analysis with the conventional treatment methods of wastewater in the CE framework. Here, the proposed lifecycle assessment for phytoremediation of domestic wastewater is presented in Figure 1 [17]. In addition Figures 2 and 3 illustrate the proposed CE models for phytoremediation of domestic wastewater.

Life Cycle Assessment of Wastewater Treatment Using Phytoremediation Techniques

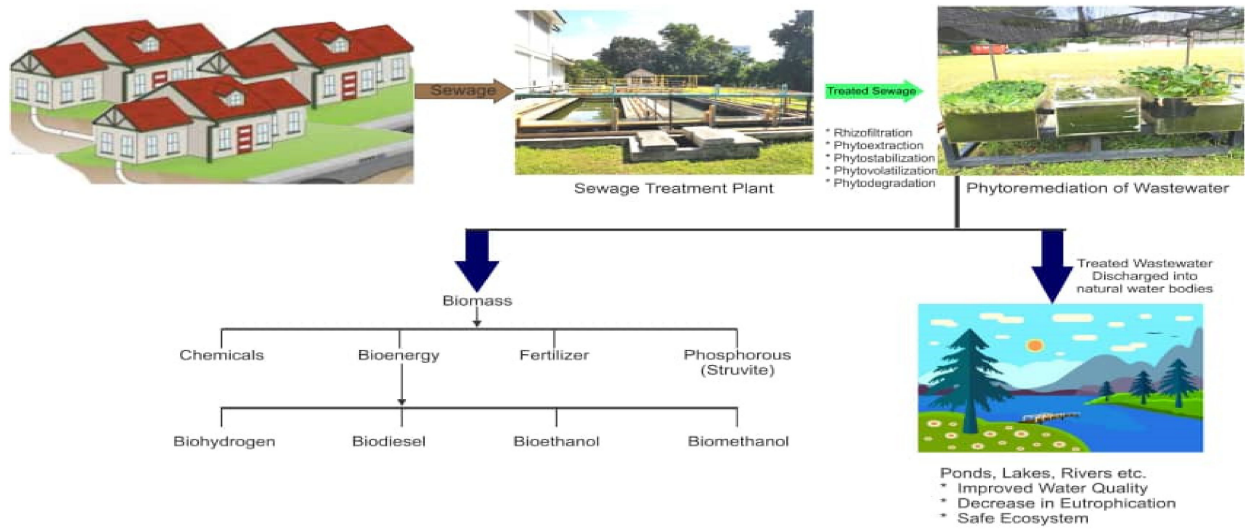


Figure 1. Lifecycle assessment of wastewater treatment using phytoremediation techniques.

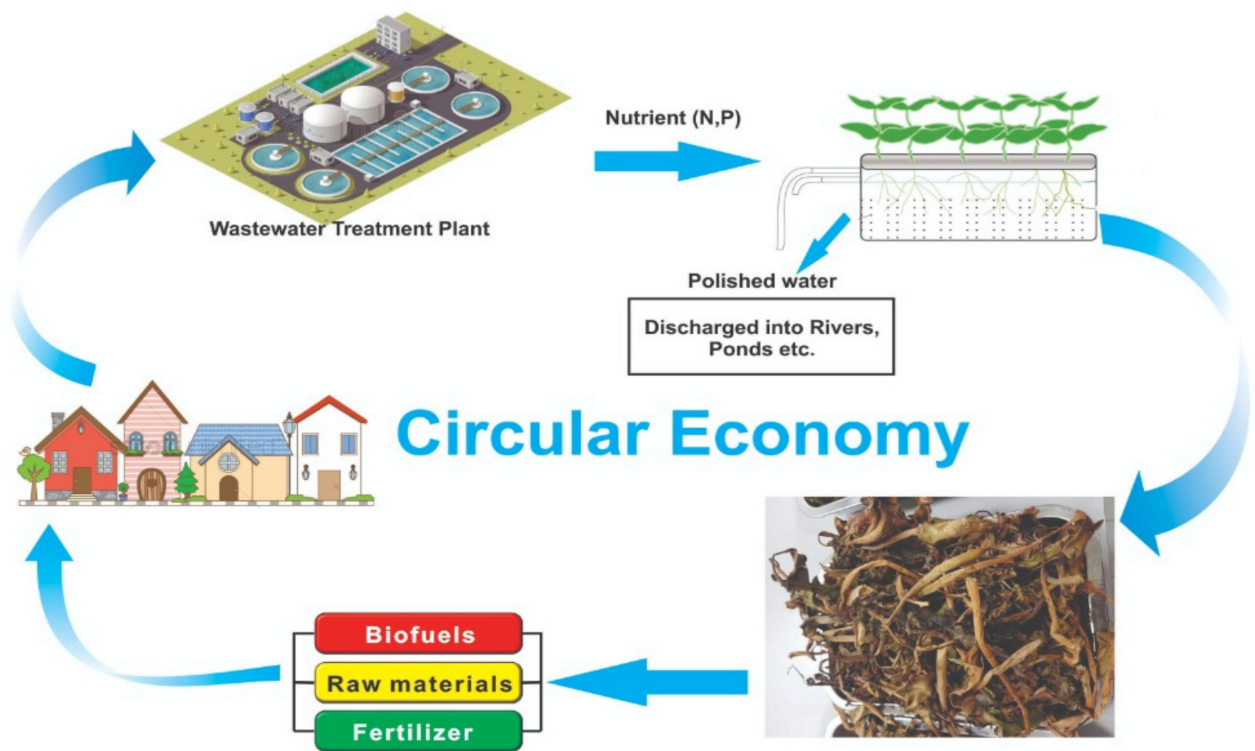


Figure 2. Circular economy model for resource recovery using phytoremediation technology.

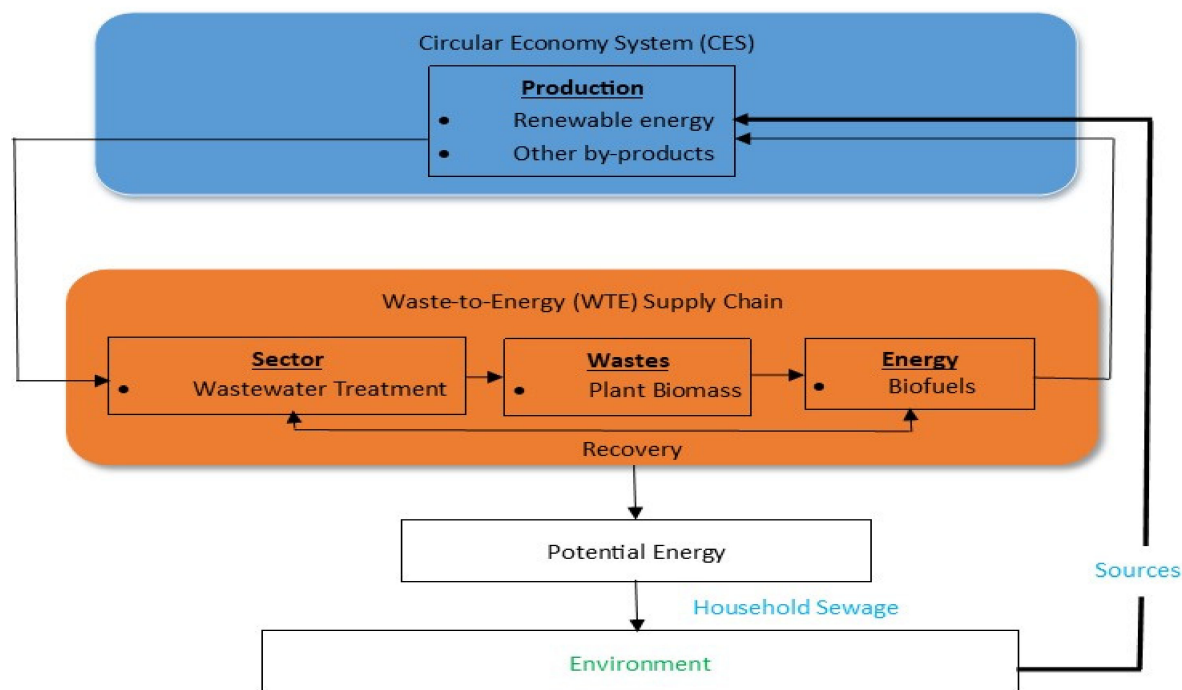


Figure 3. Relationship between CE, waste-to-energy and environment framework for phytoremediation of domestic wastewater.

3.3. Selection of Aquatic Plants for Phytoremediation of Wastewater

Among the listed aquatic plants mention in Section 2.3, three plants (*S. molesta*, *E. crassipes* and *P. stratiotes*) were selected due to their ability to acclimatize and grow well in our constructed hydroponic systems when a preliminary study was conducted. Additionally, we found that the plants were readily available. Further, it was observed that the plants could withstand the temperature of 20–35 °C and pH of 5–8. These findings coincide with the reports of Aswathy [51], who stated that *P. stratiotes* have the capability to tolerate temperatures ranging from 21 to 30 °C. Similarly, Sun et al. [52] studied ten plant species in order to select the most suitable plants for remediation of heavy metal contaminated wastewater. According to their results, *Phragmites australis*, *Acorus calamus* Linn., *Lythrum salicaria* Linn. and *Typha minima* were observed to be the most promising plants for phytoremediation of the electroplated wastewater. Besides, the economic success of wastewater treatment and energy generation using phytoremediation methods are heavily reliant on the photosynthetic activity and growth rates of the selected plants [48]. More information on the behavior of *P. stratiotes* and *L. minor* plants in our constructed hydroponic systems can be accessed online [45].

3.4. Outcome of Biomass Harvested from Phytoremediation of Domestic Wastewater

In phytoremediation of domestic wastewater using hydroponic tanks, regular harvesting of the matured plants from the cultivation systems is necessary to maintain optimal plant density [25,53,54]. Manual method through hand removal was employed in harvesting the plant biomass during the cultivation period. Biomass obtained from phytoremediation can be utilized for biofuels and energy production, paper or charcoal generation, fertilizer and food supplements. The RGR of the three aquatic plants at different retention times are presented in the subsequent sections. The pictorial diagrams of the harvested plant biomass are presented in Figure 4.



Figure 4. Harvested plant biomass.

3.4.1. RGR for *E. crassipes*, *P. stratiotes* and *S. molesta* at 24 h Retention Time

The results of the RGR evaluations for *E. crassipes*, *P. stratiotes* and *S. molesta* at 24 h retention time are presented in Figure 5. According to Figure 5, it can be seen that the test plants grow efficiently from 0 day to the 14th day. The pattern of the RGR showed that the plants tripled in weight within the 14 days of the cultivation period. *E. crassipes* recorded the highest growth with $2.5 \pm 0.03 \text{ g g}^{-1} \text{ d}^{-1}$, followed by *S. molesta* with $1.33 \pm 0.05 \text{ g g}^{-1} \text{ d}^{-1}$ and *P. stratiotes* $0.92 \pm 0.27 \text{ g g}^{-1} \text{ d}^{-1}$ at the end of the sampling period. The high density observed by *E. crassipes* could be attributed to the long roots. The ANOVA tests revealed a statistical difference between the growth rate of the individual test plants. Similarly, the high growth observed in the three plants was ascribed to the longer retention of 24 h, which provided the plants with enough time to use the available nutrients present in the wastewater as food for their growth. However, nutrient input/output and the efficient management practices need more study before considering macrophytes in phytoremediation of wastewater [44].

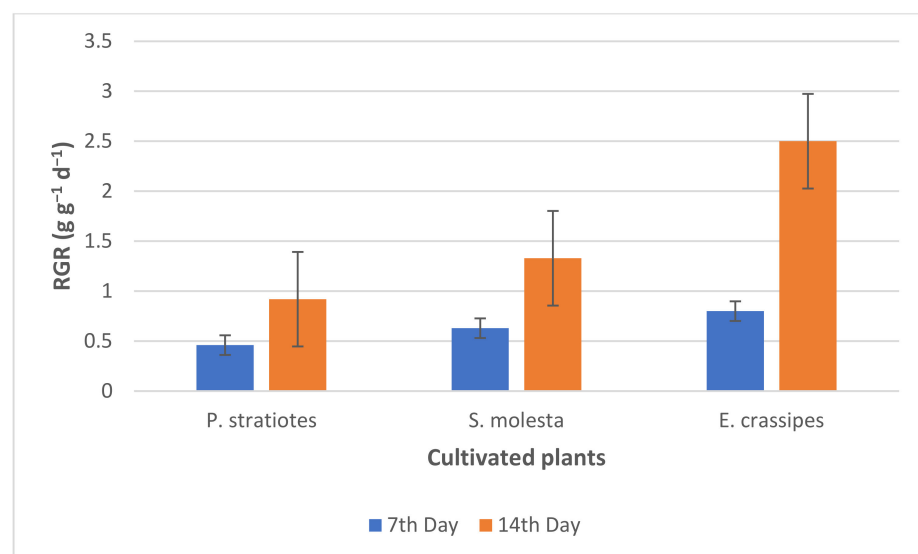


Figure 5. Graph of RGR ($\text{g g}^{-1} \text{ d}^{-1}$) against cultivated plants at 24 h retention time.

3.4.2. RGR for *E. crassipes*, *P. stratiotes* and *S. molesta* at 12 h Retention Time

The outcome of the RGR evaluations for *E. crassipes*, *P. stratiotes* and *S. molesta* at 12 h retention is presented in Figure 6. From the graph, at 12 h retention time, the outcome of the RGR for the three aquatic plants increased during the culturing period. The trend of the RGR showed that the growth rate of the *E. crassipes*, *P. stratiotes* and *S. molesta* doubled at the end of the sampling period. The RGR of the *S. molesta* increased from $0.43 \pm 0.1 \text{ g g}^{-1} \text{ d}^{-1}$ observed on the 7th day of the cultivation to $0.92 \pm 0.06 \text{ g g}^{-1} \text{ d}^{-1}$ on the 14th day; while the RGR of the *E. crassipes* plants increased from $0.85 \pm 0.1 \text{ g g}^{-1} \text{ d}^{-1}$ to $1.94 \pm 0.55 \text{ g g}^{-1} \text{ d}^{-1}$ from the 7th day to the 14th day. Additionally, the *P. stratiotes* doubled from $0.28 \pm 0.02 \text{ g g}^{-1} \text{ d}^{-1}$ to $0.61 \pm 0.05 \text{ g g}^{-1} \text{ d}^{-1}$ from the 7th day to the 14th day. These results demonstrated that the wastewater promoted the growth of the selected plants at 12 h retention time.

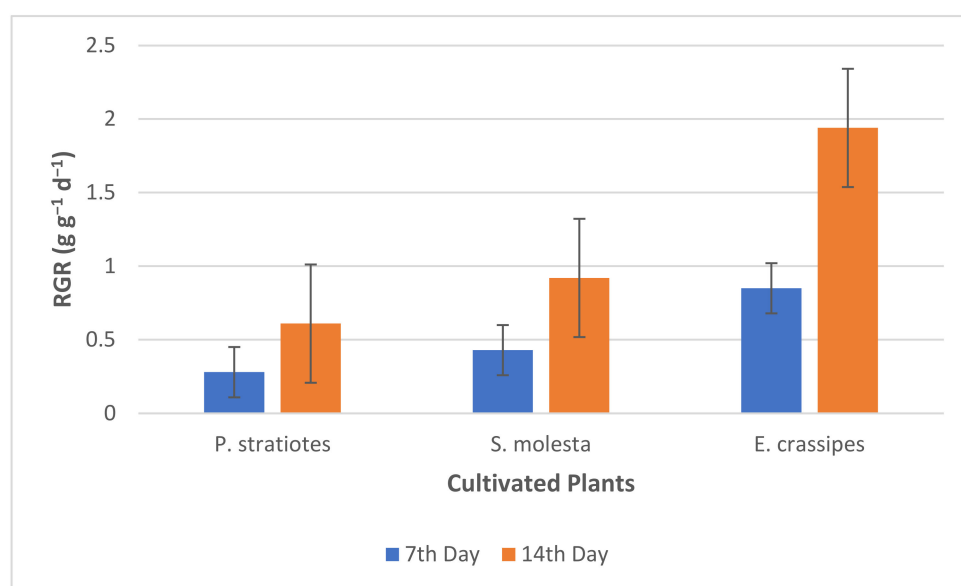


Figure 6. Graph of RGR ($\text{g g}^{-1} \text{ d}^{-1}$) against cultivated plants at 12 h retention time.

3.4.3. RGR for *E. crassipes*, *P. stratiotes* and *S. molesta* at 6 h Retention Time

The outcome of the RGR evaluations for *E. crassipes*, *P. stratiotes* and *S. molesta* at 6 h retention is presented in Figure 7. According to the graph, a slow growth rate by the three plants was recorded when compared with the growth observed at 12 and 24 h retention times. For the *P. stratiotes*, a little change from the RGR value of $0.12 \pm 0.05 \text{ g g}^{-1} \text{ d}^{-1}$ to $0.18 \pm 0.57 \text{ g g}^{-1} \text{ d}^{-1}$ was recorded from the 7th to 14th day; while for the *S. molesta* plants, a slight increase was observed in the RGR from $0.27 \pm 0.1 \text{ g g}^{-1} \text{ d}^{-1}$ to $0.53 \pm 0.33 \text{ g g}^{-1} \text{ d}^{-1}$. In the case of *E. crassipes* plants, the RGR doubled from $0.58 \pm 0 \text{ g g}^{-1} \text{ d}^{-1}$ to $1.09 \pm 0.01 \text{ g g}^{-1} \text{ d}^{-1}$. This outcome similar to what was reported by Prasetyo et al. [55] and it entails that the 6 h retention time is not conducive for the plants utilize the available nutrients present in the wastewater and grow well in the hydroponic systems.

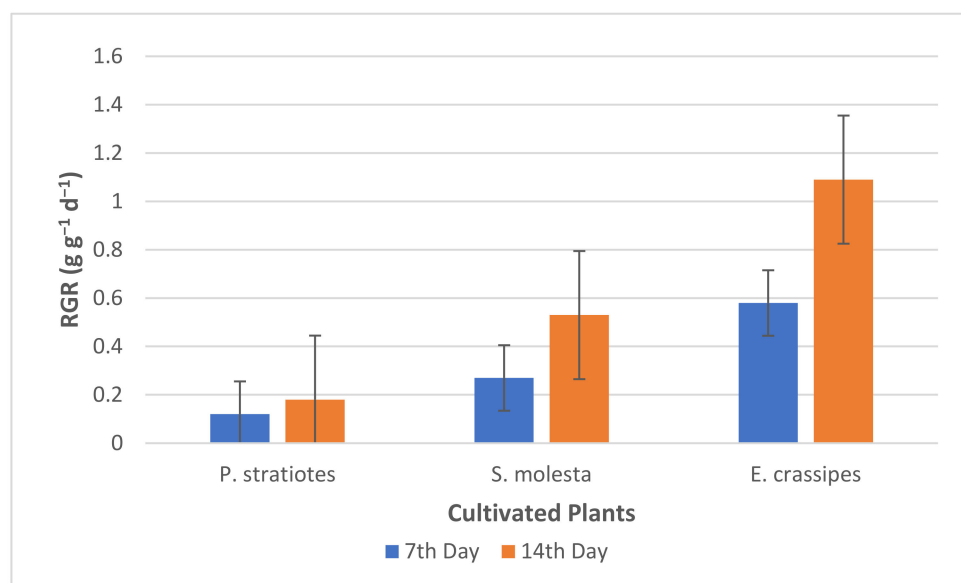


Figure 7. Graph of RGR ($\text{g g}^{-1} \text{d}^{-1}$) against cultivated plants at 6 h retention time.

4. Anticipated Challenges in Implementation of CE in Phytoremediation of Wastewater

A CE-based strategy is essential to progress towards Sustainable Development Goals (SDG). CE is centered on the conversion of waste into meaningful products and resource efficiency with the objective of promoting resource reuse. Besides, adopting the CE concept in water and wastewater treatment would help in achieving several objectives of the SDGs, as one of the critical elements of the 2030 SDG is the improvement of water quality. Wastewater is a significant input resource and its adoption into the CE context should be advocated [33]. In this light, some of the constraints that may hinder the implementation of CE in phytoremediation wastewater treatments are highlighted below:

1. Selection of suitable technology for phytoremediation of wastewater by stakeholders and industries is one of the impediments that would hinder the successful deployment of CE concept.
2. Monitoring the processes of wastewater phytoremediation requires a long time and space. Thus, there might be an inconsistent flow of valid input information.
3. Insufficient information on the capital for investment, policies and data availability are barriers that would hinder the implementation of CE strategies in wastewater phytoremediation, particularly on an industrial scale.
4. Another problem is the interdependencies between the plants, microorganisms, treatment systems and the natural environment. Additionally, integrating these essential components requires easy data exchange for proper monitoring, control and manipulations that would promote the plant growth and wastewater treatment process.
5. Lack of prior knowledge and competent human resources will have detrimental effects on the efficiency of the phytoremediation technique and, hence, CE adoption.
6. Complex methods, costs and energy involving the conversion of the harvested plant biomass into other useful beneficial products such as biofuels, bionic liquids and chemicals.
7. There is a lack of understanding and legislation that encourages the utilization of reclaimed resources. The incentives or benefits of reusing wastewater resources are not well articulated, which impedes the implementation of the CE model in wastewater treatment for energy recovery [37].

Future Perspective

In recent years, government agencies have expanded their commitment to using scientific research findings to influence policy decisions. As a result, a variety of scientific advisory systems have been established and developed throughout a number of countries [56]. Environmental sustainability, employment, healthy population and industrial processes can be obtained through a green and cleaner environment owing to academic scientific investigations that introduce new technologies and products to the market [31]. Moreover, the deployment of CE approaches in wastewater treatment and management would assist in preserving valuable resources including water, energy and nutrients while reducing pollution and waste from the environment [57]. The CE method illustrates a shift in the function of wastewater treatment systems, which has shifted from performing only the roles of wastewater treatment and disposal to an active strategy aimed at profit maximization. This repositioning will put an additional strain on traditional facilities built to satisfy water discharge limits set by law at a low cost. As a result, innovative wastewater treatment technologies could be a solid starting point for developing a more ecologically friendly water network within a regenerated water market [38]. The visible link between CE and water is the transition of WWTP to energy recovery facilities that encourages the recovery of treated water, energy, biomass and nutrients [58]. Therefore, future research should shift attention to CE measurement and application in phytoremediation of wastewater in real-life context and their prototypes which need to be proven by viable economic feasibility analysis at an industrial scale. This would promote the use of affordable and renewable biomass, growth opportunities for industries, cleaner environment, sustainable bioenergy and economic stability. Furthermore, future studies should focus on the relationship and impact of energy and water management, as well as potential improvements. The procedures should be evaluated and verified using case studies to demonstrate their suitability in different environments. Additionally, we recommend future studies in optimizing the operational processes for phytoremediation techniques of wastewater using innovative technology that will reduce the limitations associated with the techniques. This would reduce the water footprint, decrease the use of harmful chemicals and energy requirements involved in conventional wastewater treatment methods. Hence, contributing to the achievement of SDG 6, which states "Ensure availability and sustainable management of water and sanitation for everyone," as well as, to some extent, SDG 7: "Ensure that everyone has access to energy that is inexpensive, efficient and sustainable" [13].

5. Conclusions

This study would help in the reduction of the water footprint and the promotion of SDG targets in water resource management and bioenergy generation. The findings provided insights on the RGR of the plant-based biomass harvested from the phytoremediation of domestic wastewater. It also provided information on the economic and technical feasibility of wastewater phytoremediation using hydroponic tanks for simultaneous recovery of treated water and plants' biomass to enable large-scale implementation. Furthermore, optimizing resource recovery and bioenergy generation, developing new approaches and solutions, and improving process stability would help encourage and enhance the adoption of the CE framework in phytoremediation of domestic wastewater.

Author Contributions: Conceptualization, H.M.M. and G.H.; formal analysis, H.M.M. and G.H.; funding acquisition, G.H. and S.I.M.; investigation, H.M.M. and G.H.; methodology, H.M.M. and G.H.; project administration, G.H.; resources, G.H. and S.I.M.; supervision, G.H.; validation, H.M.M., G.H. and S.I.M.; writing—original draft, H.M.M. and G.H.; writing—review & editing, H.M.M. and G.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Tenaga Nasional (UNITEN) under Bold 2021 Refresh.

Acknowledgments: The authors would like to acknowledge the financial support from Universiti Tenaga Nasional (UNITEN) under Bold 2021 Refresh.

Conflicts of Interest: The authors declare no conflict of interest.

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