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Review

A Review on Uses of *Lemna minor*, a Beneficial Plant for Sustainable Water Treatments, in Relation to Bioeconomy Aspects

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Abstract: This review seeks to highlight the issue of utilizing a widely distributed aquatic species within the broader context of the transition from a linear to a circular economy and the growing emphasis on environmental sustainability. To promote a cleaner aquatic environment and ensure compliance with current regulations, the use of bioindicators and plant bioaccumulators presents a viable alternative. *Lemna minor*, a small aquatic species, serves as a noteworthy example that warrants greater consideration. A review of specialized literature was conducted to provide a comprehensive overview of these issues, drawing from the most relevant sources. This paper offers a broad discussion on bioeconomy and water management, along with an in-depth examination of *L. minor*, its characteristics, and its practical applications. The biological characteristics, ecological significance, and useful applications of *L. minor* in wastewater treatment, bioenergy, and bioproduct production are summarized in this research. The analysis also identifies research gaps for further investigation and looks at how this plant fits into new frameworks for the circular economy.

Keywords: *Lemna minor*; bioaccumulator; water treatment; environmental sustainability; low-cost water purification

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1. Introduction

Lemna minor, commonly known as duckweed, is an aquatic macrophyte with a wide range of applications in several areas, such as wastewater treatment, ecotoxicological testing, animal and human food sources, as well as the production of starch, proteins, and bioethanol [1–6]. Abdullah et al. (2014) provide a detailed analysis of different approaches to wastewater treatment, discussing both the benefits and disadvantages of each method. This can help in choosing the appropriate technology for the specific application situation [7].

There has been a notable increase in the number of publications on duckweed and the circular economy, based on data from the Web of Science Core Collection search engine (Figure 1) [8].

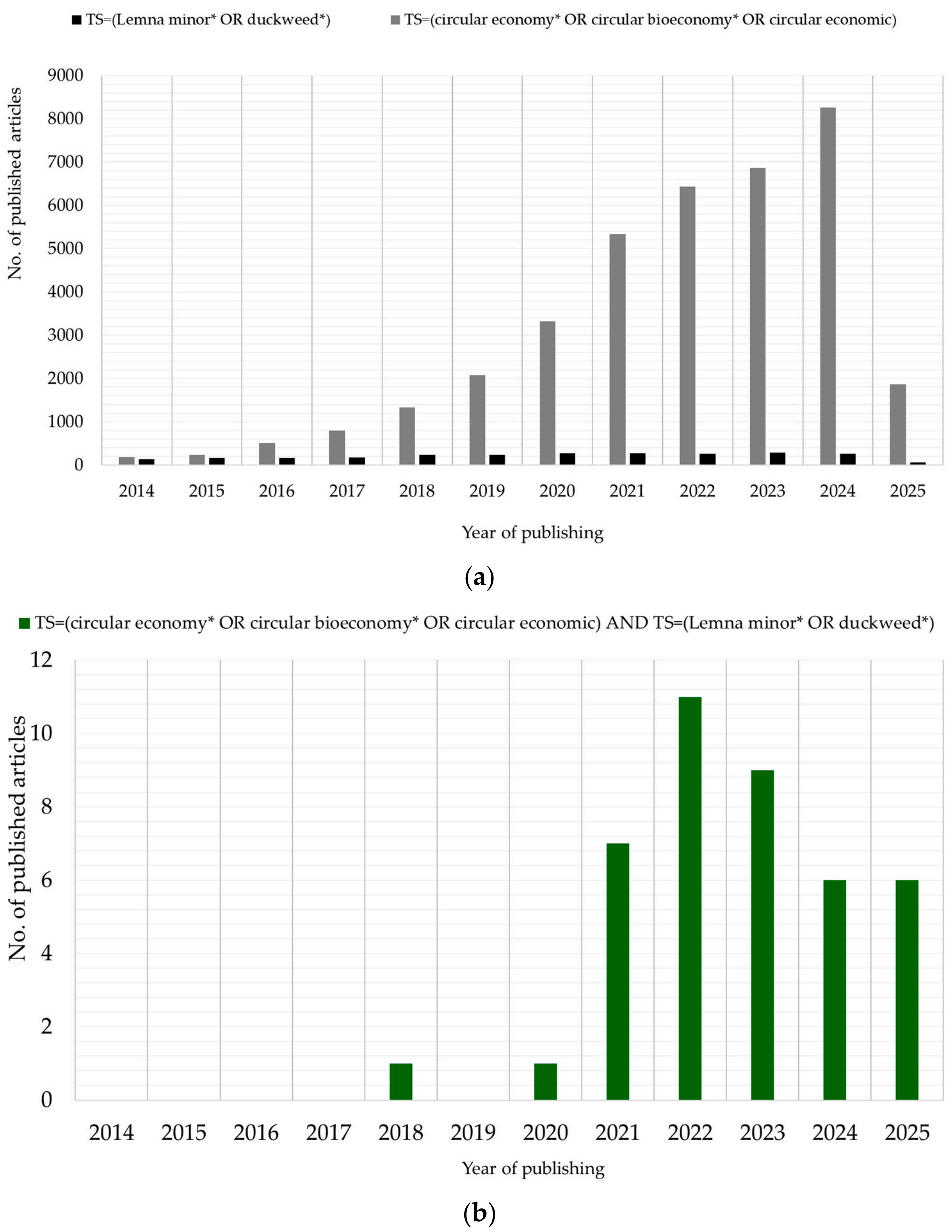

Figure 1. The amount of yearly articles that are published on the following keywords: (**a**) duckweed and circular economy, along with associated articles; (**b**) duckweed and circular economy combination.

Duckweed (search query: ”TS = (*Lemna minor** OR duckweed*)”), circular economy (search query: “TS = (circular economy* OR circular bioeconomy* OR circular economic)”), and joint articles (search query: “TS = (circular economy* OR circular bioeconomy* OR circular economic) AND TS = (*Lemna minor** OR duckweed*)”) are of current importance, as evidenced by the number of articles published annually between 2021 and 2025.

The scope of this study is to provide an overview of the utilization of *L. minor* in prospective circular bioeconomy models, beginning with the application of plants in the remediation of various types of wastewater and progressing to the reuse of these organisms for the production of biomass, starch, proteins, and bioethanol. This paper stands out for offering a thorough evaluation of *Lemna minor* as a bioresource in circular bioeconomy systems and as a phytoremediation technique. Its quick expansion and adaptability in turning waste into useful products make it a suitable model for sustainable water management in both industrialized and developing nations. The objectives of this study comprise:

1. Description of *Lemna minor* and its various applications, including wastewater treatment.
2. The review of wastewater and potential remediation techniques.
3. The outline of key aspects of circular bioeconomy.
4. The illustration of *L. minor* use in circular bioeconomy systems.

2. Materials and Methods

In order to attain the specified objectives of this review paper, several steps were completed. A systematic literature search was carried out using the Preferred Reported Items for Systematic Reviews and Meta-Analyses method (PRISMA 2020) guidelines, ensuring transparency and reproducibility. The selection process involved several steps: identification, screening, eligibility, and inclusion phases [9]. The path to follow involves the clarification of the considered research, the effective review of literature, and the reporting phase [10]. The reproducibility of this method was also highlighted in other studies related to the circular economy, such as [11,12].

The first phase, outlined in the introductory part, included the specification of the main objectives of the study, but also the aim. This part was completed by the choice of adequate keywords and the selection of the exclusion criteria, i.e., their inaccessibility in an open-access form and the unacceptability of the papers published in languages other than English and Romanian. Among the inclusion criteria, we can mention that we used data published in journals that provide a double-blind review before accepting, and which were published quite recently, except those that describe the fundamentals of the domain.

The second stage of this literature review consisted of the search for articles in relation to this theme. Web of Science, but also Google Scholar and PubMed, were the main sources for scientific research and were used for selecting appropriate literature for this analysis. The most appropriate keywords for the search were "circular economy, circular bioeconomy, wastewater, wastewater management, wastewater treatment, remediation, bioremediation, duckweed, *Lemna*, *Lemna minor*, duckweed applications/uses". A total of 125 articles were selected from Web of Science and Google Scholar. PubMed was used exclusively to generate the conceptual map in VOSviewer, and the number of articles retrieved was 25. Among these articles, those that did not best fit the purpose of this review were ignored. Nevertheless, to ensure easy understanding and provide a general overview regarding the relation of circular bioeconomy with *Lemna minor*, a logical graph was generated utilizing VOSviewer [13], based on studies published on PubMed [14].

Published data regarding the distribution of this duckweed were visualized by creating a map via the MapChart online tool [15]. These data were used to emphasize the applicability of this study, based on the worldwide spread of duckweed.

3. *Lemna minor*—Description and Applications

Duckweeds are free-floating, green freshwater aquatic plants from the Araceae family, encompassing multiple genera, such as *Lemna*, *Spirodela*, *Wolffia*, and *Wolffiella*. These organisms are among the smallest known flowering plants and are characterized by a rapid reproductive rate. Increasing scientific interest in duckweeds is driven by their exceptional capacity for nutrient removal from aquatic ecosystems, as well as their high protein content and low fiber composition, which make them valuable for various biotechnological and environmental applications [2,16].

3.1. Plant Species Short Description

The common duckweed (*Lemna minor* L.) is a small free-floating aquatic macrophyte, widely used in research (Figure 2). These plants have an oval shape and measure around 2–5 mm in length and around 1.5–3.5 mm across. Duckweeds form colonies consisting of two or more interconnected plants. The simple structure of *L. minor* is characterized by a thalloid vegetative body known as a frond, which has smooth margins and a succulent texture. A single white root, which serves as a stabilizer in the water mass, is found on the underside of the flat frond surface [2,4,17,18].

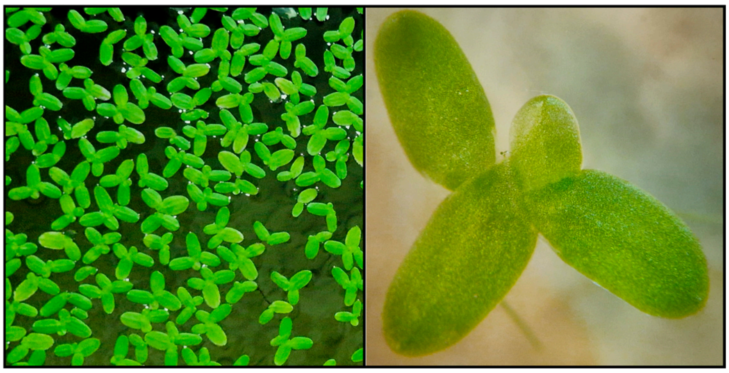

Figure 2. *Lemna minor*, the common duckweed (original photos).

The common duckweed can occupy extensive sections of the water surface because of its enormous reproductive capability, and it can be found in freshwater that is motionless or running extremely slowly, with a wide distribution worldwide (Figure 3). By sticking to aquatic birds' feathers and feet with their adhesive roots, these plants can also spread to other bodies of water [17–19].

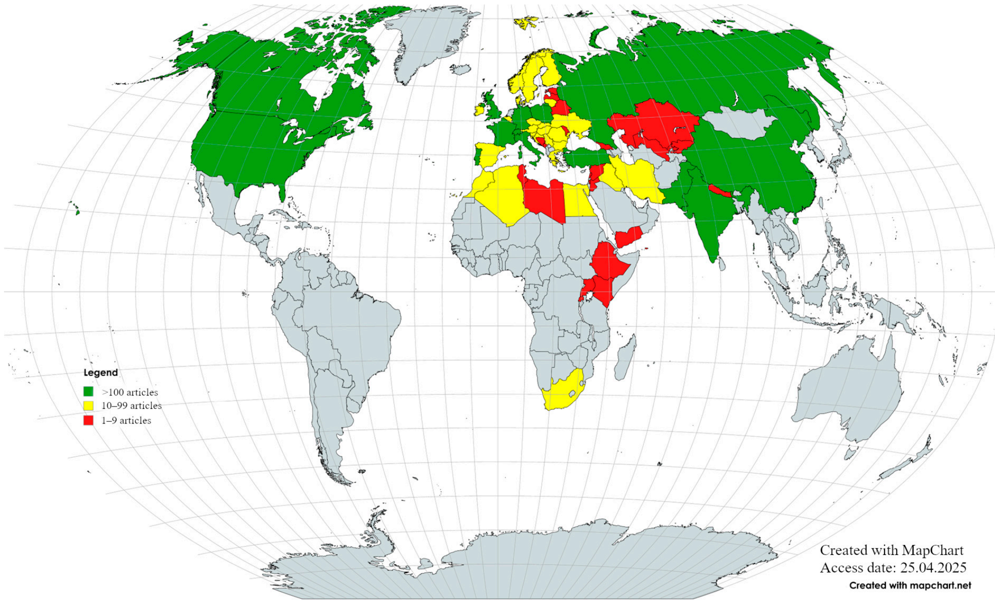

Figure 3. Global distribution of the common duckweed; the color of the country indicates the number of published articles with duckweed as a keyword on Web of Science (TS = (*Lemna minor** OR duckweed*)): green for more than 100 articles, yellow for 10 to 99 articles, and red for 1 to 9 articles. The map was created using MapChart [15] based on published data [18].

The worldwide distribution of *Lemna minor* is emphasized in Figure 3. Moreover, it is notable that the countries with abundant populations of this plant species are engaged in active research endeavors concerning its various applications.

Through the process of budding, this plant mostly reproduces vegetatively. Two lateral reproductive pockets are the site of this mechanism, which produces daughter plants that are genetically identical to the mother plant, thus forming largely clonal populations. For a brief time, offspring plants create the colonies mentioned above, remaining connected to the mother plant via thin stipes, which eventually wither. Additionally, the duckweed can reproduce by producing a single, minuscule flower that develops into a single fruit with a single seed within. Moreover, this plant has the ability to produce turions, which are starch-rich fronds that sink to the bottom until favorable conditions are restored [18,20].

3.2. Applications

There are many applications for the common duckweed, *L. minor*, including bioremediation procedures, ecotoxicity testing, animal or human consumption, starch and protein sources, and bioethanol synthesis.

These potential uses are feasible because the plant is easy to cultivate, propagates vegetatively at a very high rate, and allows for the repeatability and reproducibility of applied methods. Its use in toxicity testing is conducted on a large scale due to the availability of widely accepted standard guidelines, with a possible limitation being the testing of insoluble compounds or precipitates that do not come into contact with the plant roots. The use of *Lemna minor* biomass as animal feed or a source of starch has high potential, as biomass production is high (106 t/ha/year dry weight), especially in comparison to other agricultural plants such as wheat (3.15 t/ha/year) and corn (7.84 t/ha/year). Also, the starch content is up to 75% of dry weight. A potential limitation is the use of pollutant-contaminated plants with toxic effects on health. Regarding the use for biofuel production, the bioethanol yield of *L. minor* is 50% higher than that of corn, with complex pre-treatment processes not being required due to its lower cellulose and lignin content compared to terrestrial plants [21].

3.2.1. Ecotoxicity

Numerous ecotoxicity studies, some of which are even standardized by agencies like the United States Environmental Protection Agency (test no. 850.4400) [22], the Organization for Economic Cooperation and Development (test no. 221) [23], or the International Organization for Standardization (tests no. 20079 and 20227) [24,25], use the common duckweed as a test organism. These assays offer several benefits for aquatic ecotoxicological testing, including the ability to use homogeneous clonal colonies, direct interaction between plants and test chemicals dissolved in water, and an effortless cultivation process. This species has been employed as an aquatic ecotoxicity test organism for a variety of contaminants, such as pesticides [26], heavy metals [27,28], carbohydrates [29,30], nanomaterials [31], etc.

3.2.2. Bioremediation

Both by itself and in combination with other aquatic macrophytes, *Lemna minor* has been extensively utilized to remediate waters that have been tainted by a variety of contaminants, such as heavy metals, pesticides, pharmaceuticals, or organic pollutants. Duckweed wastewater treatment systems have been investigated for fish culture ponds, sewage-loaded ponds, raw and diluted household sewage, dairy waste lagoons, and secondary effluent [2,19].

Lemna minor, whether used alone or with other macrophytes, has been shown to be highly effective in removing organic pollutants [32]. In the treatment of municipal wastewater, duckweed outperformed conventional primary and secondary wastewater treatments, which typically achieve about a 50% reduction in biochemical oxygen demand and phosphate, achieving reductions of 94.45% and 79.39%, respectively [2].

The uptake of metals by duckweed can have variable results, ranging from minimal effects to inhibition or even death of the plant. In some cases, metal accumulation does not interfere with remediation capacity, while in others, even moderate uptake can cause inhibition that compromises efficiency. Severe inhibition is typically associated with oxidative stress and can lead to mortality. For example, high accumulation of cadmium, copper, nickel, zinc, and aluminum in *Lemna minor* has been associated with significant growth inhibition [33].

In recent years, substantial quantities of agrochemicals, including fertilizers, pesticides, herbicides, and fungicides, have been produced and applied to agricultural and aquaculture systems, with a significant proportion entering the aquatic environment untreated. Tront and Saunders (2007) investigated the uptake of 2,4-dichlorophenol by *Lemna minor* and found that, despite some inhibitory effects, the plant sequestered over 90% of the initial compound, as evidenced by the low residual levels (<10%) in tissues [34]. Wilson and Koch (2013) observed that while exposure to norflurazon severely inhibited duckweed growth, the plant recovered rapidly once the herbicide was removed [35]. Dalton et al. (2013) reported that atrazine uptake by duckweed was comparable under laboratory and field conditions, suggesting that environmental variability may have a limited effect on exposure levels [36]. In a separate study, Wang et al. (2017) found that although lactofen did not cause significant toxicity over a five-day period, its uptake by *L. minor* was minimal, suggesting low bioavailability. Taken together, these studies suggest that the common duckweed exhibits differential responses to different agrochemicals, highlighting their potential utility in mitigating water pollution [37].

3.2.3. Feedstock

Under ideal growth conditions, *L. minor* may quadruple its biomass in a matter of days, which makes it highly promising for use as animal or even human food. The quality of certain animals has been demonstrated to improve when this duckweed is added to their diet. Such studies have been carried out on various species of fish, such as common carp and tilapia, different types of poultry, like chickens and ducks, as well as on pigs and ruminants. Regarding human consumption, there are only a few studies available that highlight the content of starch, protein, and fat of duckweeds, as well as some secondary metabolic compounds with antioxidant and anti-inflammatory effects. Although there are some concerns about consuming duckweed due to potential manganese overexposure or potential allergic reactions due to the high protein content, the option of using this plant as food is not ruled out [4,38,39].

3.2.4. Protein and Starch Source

Protein makes up 20–35% of the dry mass of common duckweed, while carbohydrates only represent about 10%. The proteins are of high quality and include a variety of amino acids that are essential for human nutrition. It has been noted that this plant exhibits an under-expression of carbohydrates and starches, but their production can be enhanced by nutrition concentration, plant hormones, and light intensity. The high levels of protein and starch make them worth extracting and using in various applications, such as using protein as feed or as a supplement in culture media and using starch as feed or to produce bioethanol [6,17].

3.2.5. Biofuels and Biochar

Despite the diverse applications of *L. minor*, there remains a significant gap in the literature on the thermochemical conversion of duckweed into fuels, chemicals, and other value-added products.

Plants of the *L. minor* species with improved starch production are considered a superior source of biomass for bioethanol production through fermentation. This method entails the extraction of starch and/or the enzymatic release of glucose from cellulose and starch, followed by yeast fermentation [6,40].

Recently, Muradov et al. provided a detailed review of bio-oil production and its characterization via duckweed pyrolysis [41]. Biomass is a versatile feedstock not only for biofuels and chemicals, but also for biochar, which improves soil moisture and nutrient retention and enables long-term carbon sequestration. This dual production strategy supports the development of carbon-negative technologies [42]. In addition, biochar is often converted into activated carbon, materials valued for their stability and cost-effectiveness, which acts as an adsorbent, catalyst support, or catalyst in processes such as methane decomposition [43–45] and CO_2 reforming of methane [46–48].

3.2.6. Genetic Modification

The utility of genetically modified duckweed as a platform for commercial biomass and recombinant protein production is well established. Yamamoto et al. (2001) contributed to this field by developing an efficient genetic transformation protocol for duckweed species, specifically *L. gibba* (G3) and *L. minor* (strains 8627 and 8744). Also, a rapid method for transforming *L. minor* (8627) was introduced, a technique that holds promise for advancing automation, high-throughput screening, and industrial applications [49].

A study was carried out using only paired-end sequencing to assemble the *L. minor* genome. Based on an estimated genome size of 481 Mbp, the draft assembly covers 98% of the genome, and its protein-coding genes are comparable to those in *S. polyrhiza*. Functional annotation and comparative analysis confirmed the accuracy of the predicted genes. Consequently, this genomic resource is invaluable for elucidating the molecular biology of *L. minor* and will support future genetic improvement and biomass production applications in duckweed species [50].

4. Wastewater and Treatment Methods

One of the key problems the world is facing is the global water crisis, due to the growth of both industrial and household usage. Freshwater sources are impacted by both natural processes, such as global warming, natural deterioration, and eutrophication, and man-made processes such as pollution and overexploitation of resources. The environment and society are both negatively impacted by declining water quality, which frequently has a severe effect on public health, economic growth, and ecosystems [2,51]. Wastewater, the residual water generated through various forms of exploitation, contains diverse pollutants and requires treatment due to the chemical contamination that degrades its quality [52,53].

There are several sources of water pollution and wastewater generation, such as urban and industrial utilization (Table 1).

Treating or remediating wastewater is essential because pollutants and nutrients in untreated water can end up in the environment, where they can affect the ecosystems through direct toxic effects on the aquatic organisms or by changing the physicochemical properties of water, as well as human health [51,52].

A wide range of physical, chemical, and biological techniques, as well as their combination, are used in the conventional wastewater treatment phases and in emerging water remediation methods. Physicochemical methods such as chemical precipitation, coagulation, flocculation, and oxidation have numerous advantages as well as disadvantages due to the use of chemicals. Other methods, such as flotation, adsorption, filtration, chelating resins, incineration, and electrochemistry, have high initial cost, but also offer numerous advantages. The biological methods, such as the use of bioreactors, biological activated sludge, microbial and enzymatic treatment, or phytoremediation, also present many advantages, while their disadvantages include the necessity to ensure optimal conditions, the requirement for culture maintenance, and the complexity of the remediation processes [53].

Table 1. Comparison of different types of wastewater sources.

Wastewater Type	Key Aspects	References
Domestic wastewater	- Organic pollutants: proteins, carbohydrates, fats (human waste) - Inorganic pollutants: detergents, soaps, and other chemicals of household use - Pollutants in true solution, as well as floating, suspended, and colloidal particles of different sizes	[54]
Agricultural wastewater	- Potentially toxic chemicals: heavy metals, hydrocarbons, pesticides, and emerging contaminants (pharmaceuticals) - Biological contaminants: various pathogenic organisms (viruses, bacteria, protozoans, helminths, and schistosomes)	[55]
Mining wastewater	- Heavy metals (varies depending on the type of rock being mined and the mining processes used) - Acid mine drainage (formed by exposing mine tailings to atmospheric conditions or surface water, which can lead to the formation of sulfuric acid)	[56]
Food processing wastewater	- Organic pollutants: sugars, such as sucrose, glucose, and fructose, as well as other dissolved organic carbon sources - Source processes: manufacturing, material transportation, cleaning, sanitization, and cooling	[57,58]

5. Bioeconomy and Circular Economy Aspects in Relation to Wastewater Management

Bioeconomy is an economic model that uses renewable biological resources to provide food, materials, and energy. It covers sectors like agriculture, biotechnology, but also bioenergy, and encourages developments that aim to cut reliance on fossil resources. In fact, in addition to the bioeconomy as a new sector, supporting an alternative, circular economy based on the valorization of organic waste, this makes the bioeconomy an asset for the economy in general, as it ensures a more resilient and less affected economy at large [59,60]. Bioeconomy includes also components of chemical, biotechnology or energy industrial processes [61]. All activities that can be linked to the development of new products, as well as the conversion and reuse of natural resources, are included in the bioeconomy domain [62,63].

It is an integrative concept that brings together the circular economy thinking (reuse, recycling, recovery) with the sustainable use of biological resources (the circular bioeconomy). This strategy leads to a reduction in waste production, while the transformation of organic waste into inputs contributes to the prolongation of the material life cycle. In this way, the circular bioeconomy tackles environmental problems as well as economic potentials, which is especially pertinent for the bioprocessing of water treatment and biomass [64]. Both at the European level, as seen from strategic frameworks such as the EU 2030 Agenda, the Circular Economy Action Plan (CEAP), and the updated Bioeconomy Strategy, and at the national and regional levels, actions are being taken to move towards more sustainable models of economy. These pieces emphasize the need for loop closure for resources, reduce environmental pressures, and stimulate bottom-up approaches in bio-based industries. The reference to nature-based solutions and circular bioeconomy principles in policy fosters the implementation of nature-based solutions, like certain aquatic plant species, in wastewater treatment [64–66]. A sustainable future and the accomplishment of the Sustainable Development Goals include more and more the incorporation of circular bioeconomy in these frameworks. This notion, in the past few years, has become more and more popular. This fact can be noticed when we talk about the growing number of wastewater remediation programs [67], but also when solutions are needed to manage resource scarcity and existing climate change problems. The circular bioeconomy is increasingly being acknowledged on a global scale as a proper way to remediate problems as resource scarcity or changes on the climatic level [68].

The 2018 Bioeconomy Strategy Update [38] and the European Green Deal [37] both establish specific goals for improving resource efficiency and decarbonizing the economy via sustainable innovation. These tactics encourage the creation of green technologies that support environmental and climate goals and acknowledge the necessity of creating circular value chains based on biological resources. These policy tools offer guidance and financial opportunity for incorporating circular bioeconomy approaches in areas such as nutrient recovery and wastewater remediation [41–43]. Moreover, to analyze whether these principles are implemented and generate success, it is important to define the primary drivers and indicators for the growth of circular bioeconomical notions [69,70].

An example from Holland presents the success of the wastewater plant that is circular economy-based. There is a Treatment Plan in Amsterdam, which generates a significant amount of biogas from sewage sludge [71]. The recovered nutrients, such as the main ones, P and N, go back into agriculture, and thus an alignment with the Sustainable Development Goals can be observed [72]. This model demonstrates how developed countries are implementing circular bioeconomy solutions in wastewater treatment. In contrast, developing regions like sub-Saharan Africa face greater challenges in adopting these practices, often due to a lack of infrastructure and funding. By reducing the quantity of resources consumed per unit of production, the circular bioeconomy strategy can offer solutions to economic and environmental problems in these regions [73]. This approach is particularly relevant in waste management, where innovative strategies can transform residual biomass into valuable products. Furthermore, the notion of bioeconomy or circular bioeconomy, related to residue management, has led to new themes which should be taken into account [74,75]. The literature review concluded that while many studies were conducted to explore the potential of converting numerous residual streams into sustainable products, not so much attention has been paid to the potential of integrating wastewater treatment facilities with reactor-based feed production. Recent studies are focused on the recovery of energy and nutrients from wastewater treatment specialized plants [76].

This overview of the existing literature presents the link between bioindicators of water quality and bioaccumulators, which can be included in technologies linked to the circular economy. One of the main principles of the circular bioeconomy represents a proper combination of available resource reutilization and waste management practices [77,78]. Some authors [79] mentioned that the circular economy can massively reduce the consumption of raw products and materials, but also increase energy efficiency, which is why resource recovery is very important in wastewater treatment. According to Hoek et al. (2018), who investigate several techniques for principal nutrient recovery and their impact on sustainable wastewater treatment, the gain and reuse of nutrients such as nitrogen and phosphorus from wastewater is very crucial [72]. There are studies, e.g., Leong et al. (2021), that investigated the wastewater treatment and the potential of waste biorefineries to convert residues into useful products, such as biopolymers and biolipids [71]. Moreover, biorefinery strategies minimize waste and greatly increase resource utilization, which is in line with the objectives of bioeconomy. Additionally, new technologies such as forward osmosis membranes are quite important to the advancement of circular bioeconomy in wastewater treatment. According to Salamanca et al. (2023), forward osmosis membranes present the capability to eliminate newly discovered pollutants from urban wastewater, thus supporting the reutilization of the resources and the known sustainable practices [80]. There are various sources that state that the solution to the problems generated by pollution and water shortages is represented by the inclusion of available resources into different technologies. Moreover, methods developed in relation to biological systems, such as phytoremediation and microbial processes, have become clearly popular as a sustainable wastewater treatment option. In the framework of the circular bioeconomy, Dahiya et al. (2022) recommended the use of biological systems to advance the Rs specific for this concept, namely: reduce, recycle, and reuse [81].

Among the main links with bioeconomy, the integration of biorefineries in wastewater treatment plants should be mentioned. These allow both wastewater treatment and the production of useful co-products. Some authors presented the potential of utilizing known anaerobic digesters in wastewater treatment plants to obtain volatile fatty acids, which can represent the base for numerous biorefinery applications [82]. Thus, a contribution to the development of sustainable high-value products can be observed [71]. Additionally, microalgae play a major role in the integration of the bioeconomy into water treatment systems. As they produce biomass for material and energy purposes, they also eliminate organic pollutants and nutrients. Numerous studies emphasize their application in producing biofuels or products high in carbohydrates, as well as in cleansing wastewater from the food industry [55,56]. Additionally, struvite crystallization has been successfully achieved with magnesium-enriched biochar made from microalgae, which helps recover nutrients from wastewater streams [57]. Over 2200 km^3 of wastewater are produced annually worldwide, making up more than half of all freshwater withdrawals. Regional data show pronounced variations: With more than 230 m^3 per person per year, North America is in the lead, followed by sub-Saharan Africa (46 m^3), Europe (125 m^3), Oceania (88 m^3), Asia (80 m^3), and Latin America [58]. Global wastewater volumes are predicted to rise by more than 50% by 2050 [58]. In high-income countries, up to 70% of wastewater is treated; in low-income countries, the rate might be as low as 27–38%. In order to expand treatment capacity, it is imperative that both traditional and non-traditional treatment methods be adopted [59].

Big cities located in India produce, on average, almost 40 million liters of sewage per day (MLD), and only almost 12 MLD are treated. In addition, almost 60% of the wastewater produced by various industries was treated 20 years ago [83]. Between the methods utilized for treatment, conventional wastewater procedures can be considered energy-intensive, not cheap and need much upkeep.

Some authors presented that, because of a number of issues, such as probable inappropriate maintenance, inadequate facility design, power outages, and a shortage of skilled personnel, these water treatment plants typically remain closed [84].

It can be noticed that in the domain of wastewater treatment, seen from the circular bioeconomy perspective, microalgae and duckweed have shown great potential. Their capability to thrive in nutrient-rich wastewater allows them to simultaneously cleanse polluted waters and produce biomass that can next become biofertilizers, biofuels, or other useful goods. Recent studies mentioned the efficiency of microalgae in nutrient recovery and biofuel generation [85]. In the other paper, it was presented how algal cultivation can improve the economics of wastewater treatment through the formation of bioproducts [86].

This is further detailed in other papers, in which phytoremediation methods that use natural processes to cleanse residual water and recover various chemicals at the same time are debated.

When it comes to mechanization, scientific literature has mentioned that conventional water treatment techniques are significantly better than unconventional ones. Three basic categories may be used to classify conventional methods: primary, which includes the pre-treatment process; secondary; and tertiary [87].

Large debris and grit are removed from the raw effluent through pretreatment, whereas primary treatment procedures are often used to remove sedimentable solids and floatable particle matter. Secondary treatment, implying biological support, processes soluble organics and leads to the elimination of refractory solids as sludge.

Additional unwanted elements are eliminated using tertiary treatment procedures to meet regulatory requirements.

Unfortunately, leftover water reduces the aquatic environment's dissolved oxygen content, which has an impact on human health as well as lotic and lentic ecosystems. Furthermore, a lack of funding and technological support causes almost 50% of wastewater in developing countries to go untreated. Thus, the utilization of microalgae, duckweeds, and other biological accumulators, and the integration of biotechnological processes.

About 1% of the power used in wealthy nations like Europe comes from this kind of procedure. Modern living may be supported by wastewater treatment facilities that use the newest technology while lowering labor, energy, and power costs. Therefore, to remove these obstacles, additional nations should construct plants at a reduced cost.

To sum up, research suggests that the circular bioeconomy represents a possible initiative to enhance wastewater treatment.

Stakeholders can contribute to the development of environmentally friendly wastewater treatment systems, which can become cheaper with technique development [88].

6. Use of *Lemna minor* for Wastewater Treatment in a Circular Bioeconomy System

The following covers present research on the advantages of using duckweeds, especially *L. minor*, in circular bioeconomy applications. Due to its relatively quick growth rate, capacity to absorb pollutants, and potential for biomass valorization, *L. minor* exhibits significant potential in wastewater treatment. This species is still underutilized in many industrial processes and technologies, despite its wide range of uses. Other diverse utilities are presented in recent studies. For instance, this species' nutritional profile contains a high concentration of polyunsaturated fatty acids, particularly omega-3 fatty acids, which are critical for animal health [89]. Its capability to modify traditional feed components without the reduction of growth performance makes it a desirable alternative in aquaculture, as a protein source [90]. Beyond its role in wastewater treatment, *L. minor* also acts as a biostimulant for certain crops, enhancing growth and productivity [91]. The previously mentioned aspects, production optimization, processing, biomass generation, distribution, and consumption, are interconnected through knowledge, system development, and innovation [59].

In general, producers may consider developing a more durable system capable of maximizing resource use and reducing waste by integrating this vegetal organism into aquaculture techniques. It can be observed that the common duckweed can offer a comprehensive strategy to solve environmental problems, while also sustaining the more sustainable methods. This plant species is frequently used in biomass production, nutrient recovery, and wastewater treatment, making it a useful tool in environmental management strategies [92].

From a circular bio-economic point of view, the use of *L. minor* was mentioned as a good resource recovery plant species, being a model in various environmental management practices [93,94]. This plant species was seen as a model because of its capability in phytoremediation. Due to its ability to absorb important nutrients such as phosphate, ammonium, and nitrates, minor wood has been successfully used in wastewater treatment systems [38,95]. In addition, it is possible to convert its biomass into biogas through anaerobic digestion or to use it as a source of bioenergy and animal feed, supporting renewable resource cycles [17,96].

Lemna minor's efficacy as a biofilter is increased by its rapid growth rate, which, under ideal circumstances, may quadruple its biomass in two days [38,39]. When compared to known conventional wastewater treatments (Table 2), which are known to be expensive, *Lemna minor*-based systems can be a cheaper alternative. There are researchers who presented that such systems generate biomass that can be utilized in various ways and diminish wastewater treatment costs by 40% [38].

Table 2. Comparison of wastewater treatment/remediation techniques (BOD = biochemical oxygen demand, COD = chemical oxygen demand, P = phosphorus, N = nitrogen, TSS = total suspended solids).

Key Aspects	***Lemna minor* Phytoremediation**	**Microbial Systems**	**Emerging Chemical Techniques**	**Classical Treatment Methods**
Method overview	Utilizes *Lemna minor* to absorb pollutants from wastewater Applied in free-floating systems	Based on microbial metabolism to degrade or accumulate pollutants Include activated sludge, microbial bioreactors, etc.	Rely on chemical reactions such as oxidation and reduction to remove pollutants Involve advanced oxidation processes, electrochemical treatments, etc.	Use physical, biological (microbial systems), and chemical phases for pollutant removal Comprise sedimentation, filtration, adsorption, coagulation, flocculation, etc.
Target contaminants	- Ammonium - Dyes - Heavy metals - Microplastics - Nanomaterials - Nutrients - Organic matter - Pesticides and other agricultural contaminants - Pharmaceuticals - Suspended solids - Etc.	- Heavy metals - Nutrients - Organic matter - Pesticides - Pharmaceuticals - Etc.	- Dyes - Heavy metals - Organic matter - Microplastics - Nutrients - Pesticides - Pharmaceuticals - Etc.	- Dyes - Heavy metals - Organic matter - Nutrients - Pesticides - Suspended solids - Etc.
Economic considerations	- Low-cost set-up and maintenance - Potential biomass valorization	- Moderate cost for aeration and skilled labor - Cost-effective at large scale	- High cost for advanced materials and operation	- High initial investment - Cost-effective at large scale
Treatment efficiency as removal rates (%)	- 94.5% Cu - 90% methylene blue - 14% glyphosate - 91% BOD - 16,4 COD - 88% P - 63% TSS	- 77% Cu - 60% glyphosate - 65% COD - 19% P	- 86% Cu - 90% methylene blue - 95% glyphosate - 70% BOD - 68% COD - 85% P - 95.4% TSS	- 95% Cu - 100% methylene blue - 84% glyphosate - 71.5% BOD - 65% COD - 78% P - 96% TSS
Feasibility	- Highly feasible, but climate-dependent and requires land area	- Technically feasible with trained personnel	- Technically complex - Feasible for well-funded facilities	- Highly feasible in urban infrastructure, but requires land area and technical resources
Key advantages	- Eco-friendly - Minimal infrastructure requirements - Simple operation - Biomass recovery and valorization potential - Adaptable to different pollutants - Scalable - In temperate and tropical climates, the absence of vegetative rest allows year-round use	- Biologically sustainable - Scalable and adaptable - Good performance under controlled conditions	- Effective against difficult-to-remove contaminants - Fast acting - Suited for advanced treatment	- Proven reliability - Integrated into most urban infrastructures - Suitable for high-capacity systems
Main limitations	- Sensitive to growth conditions (temperature and light) - Requires large surface areas - Tends to form thick and dense mats that can stall the phytoremediation process	- Sensitive to toxic load - Requires regular maintenance and aeration - Continuous monitoring required	- High energy and material demands - Potential by-product toxicity - Not always cost-effective - Requires specialized equipment	- Limited for emerging trace contaminants such as pharmaceuticals - Ineffective for micropollutants - High sludge production - Infrastructure-dependent

Table 2. *Cont.*

Key Aspects	*Lemna minor* Phytoremediation	Microbial Systems	Emerging Chemical Techniques	Classical Treatment Methods
Applicable wastewater types described in scientific literature	- Agricultural wastewater - Aquaculture ponds - Food industry effluents - Industrial effluents - Mining polluted streams - Sewage - Textile and tannery industry effluent - Etc.	- Hospital discharges - Industrial effluents - Sewage - Textile industry effluents - Etc.	- Agricultural wastewater - Hospital discharges - Industrial effluents - Sewage - Etc.	- Construction industry effluents - Industrial effluents - Sewage - Textile and tannery industry effluents - Etc.
References	[19,21,94,97–110]	[111–117]	[118–127]	[128–136]

Table 2 presents a comparison of four main wastewater treatment methods, namely *Lemna minor* phytoremediation, microbial systems, emerging chemical techniques, and classical treatment methods. These approaches are analyzed in terms of feasibility and performance aspects. All four methods target a wide range of pollutants, with *L. minor* phytoremediation addressing a broader spectrum. From an economic perspective, the *L. minor* method is the most cost-effective, followed by microbial systems. Phytoremediation outperforms other methods in removing BOD and phosphorus, with comparable efficiency for copper and methylene blue. Emerging chemical techniques are most effective for glyphosate, while all methods perform similarly for COD, except duckweed phytoremediation. Physicochemical techniques are most effective for suspended solids.

All four methods are highly feasible, but under specific application conditions and infrastructure. *L. minor* phytoremediation stands out for its ecological compatibility and simplicity, microbial systems for adaptability and sustainability, emerging chemical techniques for rapid and high-performance treatment, and classical methods for their integration into urban wastewater frameworks and reliability. Despite the advantages of each method, they also present a range of drawbacks that must be considered when selecting a remediation method, especially since these methods can be applied to a wide range of wastewater types.

Several other aquatic plants are also utilized in wastewater phytoremediation, such as other species of *Lemna*, pennywort (*Hydrocotyle umbellate*), and water hyacinth (*Eichhornia crassipes*), which have been shown by the United States Environmental Protection Agency (US EPA) to be successful in treating wastewater in single ponds. Other aquatic plants were also used in different wastewater bioremediation studies, such as *Azolla* species, *Ceratophyllum demersum*, *Chara* species, *Hygrophila polysperma*, *Ipomoea aquatica*, *Pistia stratiotes*, *Potamogeton* species, and *Salvinia herzogii* [2].

These phytoremediation methods that use different aquatic plants differ from each other in terms of effectiveness and potential for use in a circular bioeconomy system. As observed from the data presented by Sayanthan et al. 2024, *Lemna minor* shows strong phytoremediation potential for Cu (91%), Mn (89%), and Zn (91%), making it highly effective for these metals. It also performs moderately for Pb (79%) and Co (72%), but poorly for Cr (29%) and As (5%). Compared to other aquatic plants, it is less versatile but excels in specific areas, especially when contrasted with *L. gibba* and *E. crassipes*. Its rapid growth and high uptake efficiency for select metals make it a valuable asset in circular bioeconomy systems. *L. minor* shows the highest uptake of Phosphorus (P—77%) and a strong accumulation of Nitrogen (N—53%), outperforming *E. crassipes*, *A. filiculoides*, and *A. pinnata* in phosphorus removal efficiency. The biomass productivity for *Lemna* sp., *Eichhornia* sp., and *Azolla* sp. are 324 tons/ha/year, 181 tons/ha/year, and 72 tons/ha/year, respectively. These values represent the mean productivity for each species, highlighting *Lemna*'s superior potential for large-scale application in circular bioeconomy systems [137].

The ability of duckweed to transform waste into valuable resources exemplifies how a small aquatic plant can support a circular bioeconomy [138]. *L. minor* has good nutrient removal efficiency contributes to the reduction of the environmental effects of wastewater discharge. This aligns with the fundamental principles of circular bioeconomy [139].

However, implementing circular bioeconomy models in wastewater treatment requires a deeper understanding of potential challenges. Among the challenges mentioned by Neczaj and Grosser are the necessity of coordinating policies and integrating resource recovery and energy generation into urban wastewater treatment systems [140]. Some authors suggested new techniques and multi-process systems to increase resource recovery from organic residues and wastewater [141].

To fully harness the benefits of a circular bioeconomy in wastewater treatment, further research and innovation are essential to overcome existing challenges.

According to some studies, *Lemna minor* has strong phytoremediation capabilities, successfully accumulating heavy metals such as copper, zinc, and cadmium. This makes it a bioindicator and a bioaccumulator [142,143]. By converting residues into reusable resources, the incorporation of duckweed species into phytoremediation techniques can enhance the recovery of important metals from polluted water bodies [144]. These data have implications for the creation of integrated multitrophic aquaculture systems, where *Lemna minor* can be used to recover nutrients from aquaculture effluents and improve water quality [90].

Scaling up *L. minor* for large-scale wastewater treatment presents challenges, including policy integration and flexibility. Successful implementation requires collaboration between researchers, industries, and policymakers [140].

A model for *Lemna minor* integrated in a circular bioeconomical system can be observed in Figure 4.

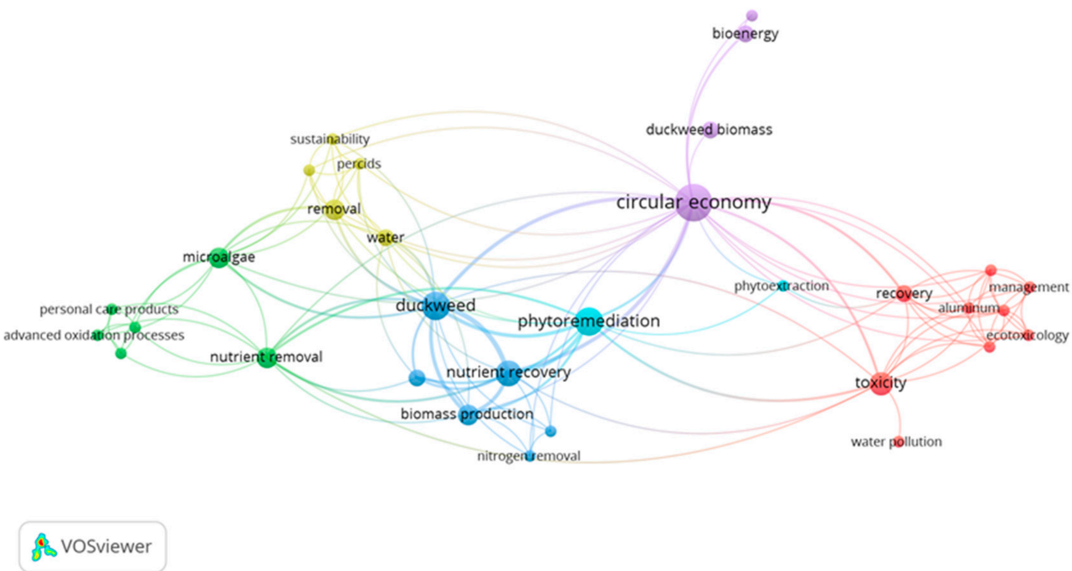

Figure 4. Map of key points for the links between circular bioeconomy and *Lemna minor* [13].

Figure 4 depicts the keywords related to circular bioeconomy and their connections, including those related to duckweed. The "circular economy" is the main focus, and it is closely related to ideas like "duckweed biomass" and "bioenergy", which highlight the plant's potential for producing renewable energy. Duckweed is recommended for nutrient removal and biomass reuse in another significant cluster that focuses on "phytoremediation" and contains terms like "nutrient recovery", "biomass production", and "nitrogen removal". Furthermore, "toxicity" is the focus of a distinct cluster that is strongly associated with "water pollution", "recovery", "aluminum", and "ecotoxicology", showing worries with water pollutants and remediation techniques. In addition, in Figure 4, *Lemna minor* appears related to "bio-hydrogen waste" and "advanced oxidation processes". Color-coded clusters can be explained by the appearance of different colors representing groups of related terms. The dimensions of the nodes and the thickness of the edges indicate the significance of the connections.

With the help provided by the visualization of this graphical representation, it becomes easier to generate a framework for a better understanding of these processes.

The future prospects for *Lemna minor* in bioremediation and circular bioeconomy applications are highly promising, although scalability remains a potential challenge. This method could integrate efficiently into existing systems or function within new ones due to its ease of handling and cultivation, low maintenance requirements, and rapid vegetative propagation. However, regulatory support will also be necessary. There is significant potential for commercialization, particularly through its biomass, which can be used as biofuel, animal feed, or a nutrient source, although optimizing harvesting methods is required. Addressing and improving these aspects will help unlock the full potential of *Lemna minor* usage.

7. Conclusions

As an approach that leads to a healthy environment, the circular bioeconomy combines the principles of the circular economy and the bioeconomy, acquiring a lot of attention in the world, and also in the European Union, and contains ideas suitable for water treatment, among others. The aim of this study was to create an insight into wastewater in general and in relation to duckweed, in the context of the circular bioeconomy. Some organisms, and this species in particular, can be used as cheap and environmentally integrated alternatives in both phytoremediation, biomass production, wastewater treatment and remediation, as a good bioindicator of aquatic environmental quality, and as a source of nutrients.

The *Lemna minor* phytoremediation method offers a highly effective and cost-efficient solution for wastewater treatment. It is ecologically compatible, making it an environmentally sustainable choice. This method is particularly beneficial in areas where simplicity and low maintenance are key factors. Additionally, it can be integrated into circular bioeconomy systems, offering multiple post-treatment applications such as biomass for feedstock, protein and starch source, and the production of biochar and biofuels, or other value-added products. Practically speaking, current research indicates that systems based on *Lemna minor* can lower the phosphorus content of treated water by more than 79% and the biochemical oxygen demand (BOD) by up to 94% [2,69]. Additionally, the biomass of *L. minor,* which is high in protein (20–35%) and starch, has shown promise in the production of animal feed, biofuels, and bioplastics. When compared to traditional approaches, these technologies have been shown to reduce treatment costs by as much as 40% when used.

In addition, the use of visual tools, such as VOSviewer and MapChart, enhances the literature review by facilitating synthesis and conceptual mapping. MapChart provides a geographical representation of the distribution of research, improving understanding of the structure and trends in the field, and VOSviewer allows visualization of relationships between concepts. These tools are rare in traditional reviews, but they offer a significant advantage in clarifying and interpreting data. In addition, PRISMA, thanks to its well-organized structure and clear definitions, allows for easy replication of such an analysis, as well as the extension of the study in different contexts, whether institutional or geographical, providing a solid basis for future research on similar topics. However, in order to preserve scientific rigor and thematic coherence when combining data from many domains, such as environmental engineering, plant biology, and policy research, a careful selection of sources was necessary. Even so, there are still some unanswered questions. To evaluate *Lemna minor*'s viability and effectiveness in large-scale phytoremediation applications within circular bioeconomy systems, more investigation is required. There are not enough research specifically addressing long-term sustainability, scalability, and implementation logistics.

Furthermore, we consider its inclusion in various other studies, but also in industrial treatments, as it is a common and generally tolerant species, thus stimulating more environmentally friendly water reuse. Wastewater management is of particular importance for many communities in developed and developing countries, and finding efficient, convenient, and easy solutions is or should be of real interest to all stakeholders involved. To address existing knowledge gaps in areas with restricted access to high-tech solutions, future research should concentrate on expanding pilot systems, improving biomass processing, and incorporating this species into multipurpose circular economy initiatives.

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