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Review

Alternative Uses of Water Hyacinth (*Pontederia crassipes*) from a Sustainable Perspective: A Systematic Literature Review

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Abstract: Water hyacinth (*Pontederia crassipes*) is a floating hydrophyte plant considered one of the 100 most harmful invasive alien species in the world. Its main uses have been developed along three lines: (1) control, (2) eradication, and (3) wastewater bioremediation. The objective of this work was to conduct a systematic literature review (SLR) focused on the documented uses of *Pontederia crassipes*, and to determine if there is evidence of its use as a raw material (plant biomass) for the generation of biodegradable products. This systematic literature review was conducted in six international databases, considering three inclusion criteria and three exclusion criteria. The available information about *Pontederia crassipes* showed a small percentage of studies aimed at the use of its biomass as a raw material for the creation of various biodegradable products, such as cardboard, paper, packaging and some other products, since this species is adaptable and prolific in multiple regions of Mexico.

Keywords: aquatic ecosystems; plant biomass; invasive species; biodegradable products

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1. Introduction

Pontederia crassipes [1], also known as water lily, water hyacinth, camalote, water flower, water drum, lechuguilla, nymph, or huachinango, is a floating aquatic species originating in the Amazon basin (mostly in Brazil). It is distributed throughout much of the world [2], as it has been documented in America (Brazil, Chile, Venezuela, the United States, Mexico), Europe (mainly Portugal and Spain), Asia (China, Indonesia), Africa (Nigeria and Ethiopia, among others), and several tropical regions of Oceania [3–5]. Due to its easy adaptability to different bodies of water, its quick growth, and wide dispersal, the *Pontederia crassipes* has been listed by the US Fish and Wildlife Service, among other institutions worldwide, as one of the 100 most invasive and harmful exotic species in the world [3,6–9].

Pontederia crassipes proliferates in rivers and lakes in 29 of Mexico's 32 states, which is equivalent to an area of approximately 50,000 hectares [4]. In most of these places where it is found, it is reported to generate problems due to its high dissemination and excessive reproduction that exceeds the limits of control and management for bodies of water [10]. Some of the effects considered negative of *Pontederia crassipes* are: (a) its rapid adaptation and growth rate in water bodies pose a great threat to any aquatic environment [11], (b) its dense colonies generate decreased water flow, reducing light and decreasing dissolved oxygen in the water bodies it inhabits generating mortality in fish species, such as snook, tilapia, and sea bass, especially in places where a bloom of *Pontederia crassipes* was generated [2,12], and (c) it obstructs the natural flow of water, smooth navigation, commercial fishing, and can damage hydroelectric systems [11,13,14]. In this context, crushing machines are used to remove and control it, clearing one hectare of *Pontederia crassipes* at a cost between 3465 USD and 4950 USD (approximate costs) [13,14].

As a particular example, in the María Lizamba lagoon in the municipality of Tierra Blanca, the Government of the State of Veracruz, Mexico, through the Procuraduría Estatal del Medio Ambiente (State Environmental Prosecutor's Office) (Figure 1), invested 1,979,953 USD. The goal was to extract 4000 tons of *Pontederia crassipes* in 483,000 m^3 of water, obtaining a cost per ton of 495 USD, and also having in mind to propose the extracted plants as a usable product [15]. However, to date no results have been reported from the harvesting program mentioned above.

Figure 1. *Pontederia crassipes* in water bodies, in addition to works of the program for the control, eradication, and sanitation with heavy machinery in the lagoon of María Lizamba in Tierra Blanca, Veracruz, Mexico. Source: [15].

In this context, in order to balance the proliferation of *Pontederia crassipes* without harming its prevalence as a species, it is necessary to know the scientific studies and uses proposed in the published literature, focusing on those that intend to give it a sustainable use. The composition of water hyacinth, according to [16], contains 92.8 to 95% water, 4.2 to 6.1% volatile compounds, 18.2 to 19% cellulose, 48.7 to 50% hemicellulose, 3.5 to 3.8% lignin, and 13 to 13.5% crude protein, so it can be used in a wide variety of processes. It should be considered that these concentrations can vary depending on the geographical area and climatic conditions. The objectives of this work were: (a) to investigate the documented uses of *Pontederia crassipes*, (b) to determine if there is evidence of its use as a raw material for the generation of biodegradable products (cardboard, pellets, packaging) using its plant biomass, based on the abundance of the species, and (c) establish the possible potential uses that have not been exploited and thus mitigate the negative impact on aquatic ecosystems.

Proposed studies for the control of *Pontederia crassipes* were taken as background, including various alternative uses of its biomass, such as energy production by combustion [17], a dye remover in wastewater [18], an alternative fuel source [11,19–21], and a reinforcing component in the production of bioplastics [21], the above with the aim of taking advantage of its high reproductive capacity. However, it is important to note that most scientific studies focus on the detection, control, and eradication of *Pontederia crassipes* [3,5,10,22–25] seeking to reduce the environmental impacts it causes.

Therefore, we aim to carry out this research with the expectation that there is insufficient evidence in the SLR about the documented uses of *Pontederia crassipes* as a raw material in the generation of alternative biodegradable products.

2. Materials and Methods

The systematic literature review (SLR) consists of conducting a search and analysis of published documents from the determination of strategies, techniques, and resources [26] and selecting articles that meet the following selection and exclusion criteria (Table 1). These criteria refer only to the use and impact of *Pontederia crassipes* in the title or abstract; only open access articles were considered due to the limited access to paid databases in Mexico. They were categorized by a thematic classification of *P. crassipes*, to finally show a result and research proposals.

Table 1. Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Refers only to the use and impact of *Pontederia crassipes* in the title or abstract.	*Pontederia crassipes* is only mentioned as an example but is not the focus of the article.
Publications of the last 5 years on *Pontederia crassipes*.	It is a poster, news, video, or conference that does not correspond to scientific research.
It is national, international, preferably in English or Spanish.	Articles' access is only by payment.

Therefore, information was sought in the scientific research databases Scopus, Science Direct, Scielo, Springer Link, Dialnet, and Google Scholar, published during a five-year interval (2016 to 2021) looking for the most recent studies. The SLR was organized as shown in Figure 2, which was developed in the following phases: (a) planning, (b) literature search, (c) critical assessment, (d) extraction of data, and (e) results.

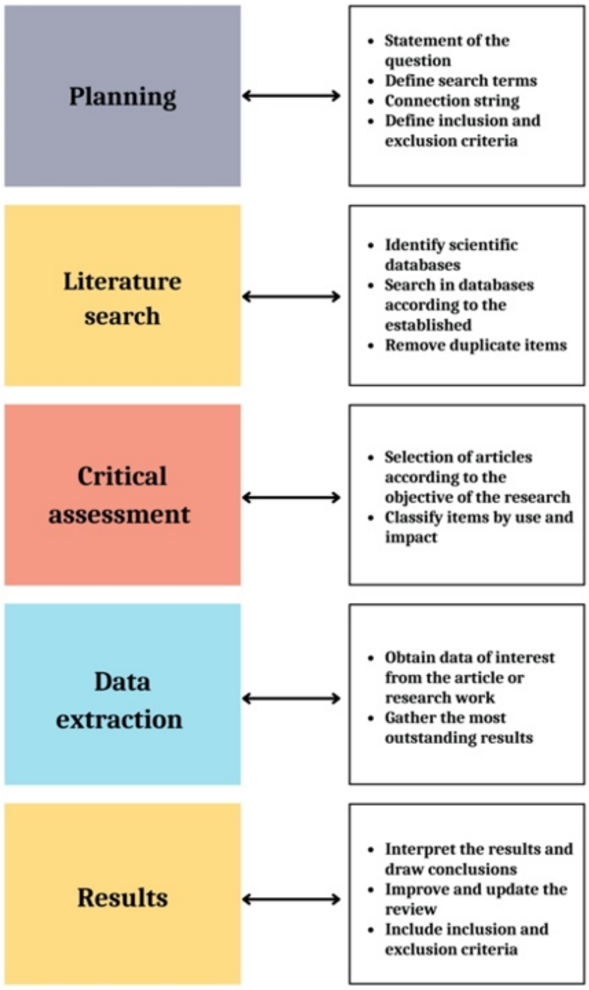

Figure 2. Process of elaboration of a systematic review. Adapted from: [26].

The planning consisted of answering the research questions RQ1: What are the main thematic studies on *Pontederia crassipes*? RQ2: What are the results obtained regarding the sustainable use of *P. crassipes*? RQ3: Which are the countries where most studies on *P. crassipes* have been carried out? and RQ4: What are the scientific studies in which *P. crassipes* has been used for the generation of biodegradable products?

Two search terms were defined, first the scientific name of the plant "*Eichhornia crassipes*" as a keyword and second the search string, in order to maximize the literature exploration on the use and impact of *P. crassipes* (formerly *Eichhornia* sp.). For this purpose, the keyword was combined with the names or synonyms as known in some endemic regions and the Boolean operator "OR". Thus, it is understood that an article only had to include some of the words to be retrieved in order to identify relevant papers and thus collect significant data of interest. Similarly, inclusion and exclusion criteria were established (Table 1) in order to review the information and extract the relevant data. Subsequently, a classification was made based on the uses and impacts of *P. crassipes* to obtain information related to product development and the generation of biodegradables products, in order to optimize the analysis and interpretation of the results of the literature review.

For data collection, a database was created with the following categories: (1) general table, which presents the quantitative results of the search in the digital research database; (2) searches, containing information of the articles included for the systematic review, which was classified as follows: 1.—Consecutive number, 2.—Title, 3.—Country of origin, 4.—Thematic classification (environmental, economic, social, medicinal, food), 5.—Use, 6.—Reference, 7.—Main results.

3. Results and Discussion

The initial data research showed 4275 articles. This research was carried out based on the keywords and on the search string that are presented in the PRISMA flow diagram, which was used for the selection of the SLR (Figure 3). Afterwards, a total of 132 articles were preliminarily selected and evaluated according to the topics of interest and the relevance for this study, such as food, environmental, economic, and medicinal (critical assessment, see Figure 2). Furthermore, these 132 articles were analyzed by reading them one by one in order to weigh and discriminate according to the search criteria necessary for this investigation (data extraction). As a result of the analysis, 37 articles were selected (results; see Figures 2 and 3).

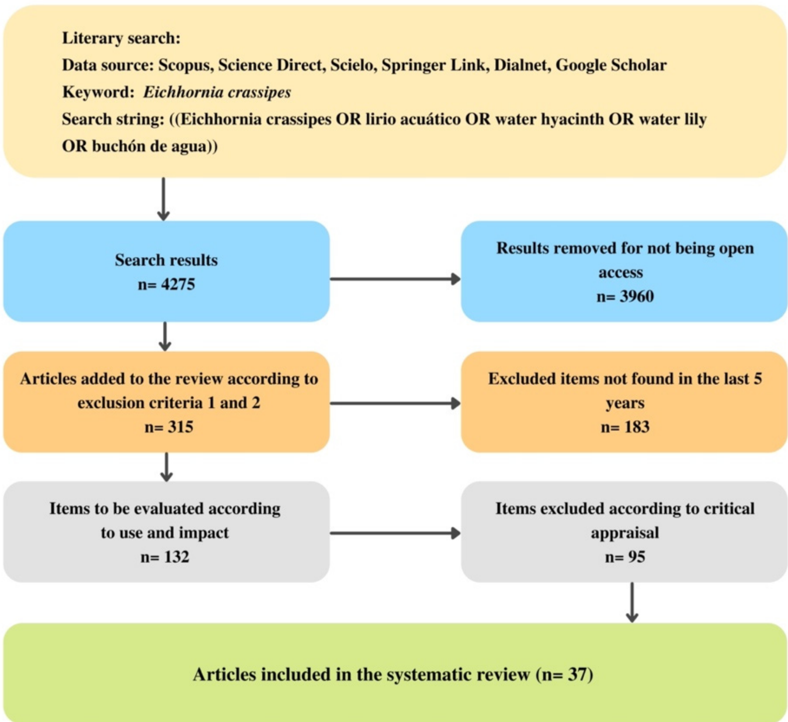

Figure 3. Flow chart of item selection and discrimination criteria.

3.1. Propagation Control of *Pontederia crassipes*

The research works related to propagation control were classified in Appendix A, Table A1, where it was identified that *P. crassipes* can spread easily due to its high adaptability to different aquatic environments worldwide, it is stated that climate change has been a modulating factor in its propagation. In this direction, the global impact of climate scenarios projected for the year 2080 on the potential distribution of *P. crassipes* in the northern hemisphere highlights that it will expand its range northward as cold stress limits are exceeded, in North America, Europe, and northeastern China [27].

On the other hand, ref. [28] conducted experiments in Brazil, in the Amazon plains, where they used *P. crassipes* to evaluate the effects of the combination of temperature and increased CO_2 on growth, physiology, and ecological interactions. They concluded that global climate change may alter the composition, biomass, and ecological interactions of Amazonian aquatic plant species.

In the case of Australia's Mungalla wetlands, east of Ingham in north Queensland, weed abundance and water quality appear to oscillate depending on summer rainfall as changes in hydraulic pressure stop or allow seaward input [29]. These studies focus on providing biological inputs for the eradication of *P. crassipes*, without contemplating a use appropriate to the conditions of their countries.

However, in the research works related to the propagation control of *Pontederia crassipes* were determined that biological control with insect herbivores may be appropriate because during the *P. crassipes* biomass decay season, herbivore decline could be related to the homeostatic capacity and adaptations of herbivores to winter climatic conditions [30]. In addition, herbicides with the active ingredient diquat can be applied in droplets that provide greater potential safety in the aquatic environment for the control of *Pontederia crassipes* [31], or these weeds can be harvested to convert them into compounds that imply improvements in agricultural production, in water quality [32], while it can also generate biomass for biofuel production [33] or can be used as a source of agricultural fertilizer or handicrafts [34].

3.2. Uses of Plant Biomass from Pontederia crassipes

Appendix A, Table A2 shows the studies related to the utilization and transformation of *Pontederia crassipes* as biomass, characterized by a high content of useful plant material in both thermochemical and biochemical processes [35], despite being considered as one of the worst weeds in the global aquatic ecosystem [3,6,8]. In turn, it can also be a potential biomass resource available in many tropical regions of the world, which, coupled with adequate technical knowledge can be used as a feedstock for small-scale production of fuel ethanol [36].

On the other hand, some studies were related to the transformation of *Pontederia crassipes* in specific issues, such as vegetative development and stem growth, and it can transform free copper ions into less toxic forms by organic complexation [13,37], and remove contaminants such as copper and lead. The advantages of using biomass for biofuel or fine chemical production were investigated by [38]. Ref. [39] studied the behavior of ceramics incorporated with fuel residues (*Pontederia crassipes* dry biomass) and flux residues (granite), as well as mixtures of both residues and obtained as a result that the high calorific value of biomass residues represents a great possibility of energy saving for the firing process.

3.3. Pontederia crassipes and Its Use as Biofuel

The works reviewed in Appendix A, Table A3 correspond to the generation of biofuel from *Pontederia crassipes* biomass. Ref. [21] conducted studies in which they determined that the dominant elements are oxygen and carbon. Since the biomass of water hyacinth has relatively high volatile content and low calorific value, it is reasonable that water hyacinth can suitably be used for combustion with coal increasing the reactivity of coal during the combustion process [21].

Ref. [19] mentions that water hyacinth is one of the alternatives of agricultural residues that can be used for biogas due to its high hemicellulose content possibly having an effect on biogas production.

Another important aspect in the use of fuel is to take full advantage of the plant biomass, therefore [40] designed a phytoremediation process using biomass of *Pontederia crassipes* (live and dead), a biofuel production process composed of the hydrolysis bioreactor along with bioreactors for the production of bioethanol and biohydrogen. Therefore, it determined that it is feasible to create and build a large-scale bioethanol and biohydrogen production system from *P. crassipes* biomass (loaded or not with heavy metals).

3.4. Pontederia crassipes and Its Use a Bioplastic and Biocomposites

Plastic is widely used in many applications, including its use in food packaging, electronic components, and automotive dashboards. Generally, plastic is manufactured from crude oil; however, plastic has a negative impact on the environment because it is not degradable and pollutes air, soils, and water bodies [41].

In Appendix A, Table A4, the results of the use of *Pontederia crassipes* as a bioplastic are shown, in which its cellulose has an important use for the preparation of bioplastic. Ref. [42] conducted studies in which it was successfully isolated by the bleaching method at low temperatures with a maximum yield. In addition, they employed a method to isolate cellulose from plants and use it as a reinforcing component in the production of bioplastics. In their results, they determined that the bioplastic prepared using starch showed better performance, such as higher strength, and degraded more easily compared to the other bioplastics prepared under different conditions, including starch bioplastic without added cellulose [41].

3.5. Main Findings on Pontederia crassipes

RQ1: What are the main thematic studies on *Pontederia crassipes*?

The literature review showed that the main topic of the research articles is approached from an environmental perspective, in relation to the propagation control, in which the authors propose the use of *P. crassipes* as biomass and the possibility of generating biodegradable products, such as fuel, biocomposites, bioplastics, and bioethanol (Figure 4).

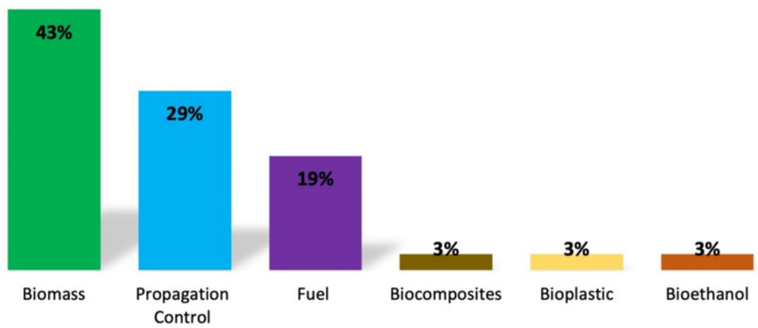

Figure 4. The main topics addressed on *P. crassipes*.

RQ2: What are the results obtained regarding the sustainable use of *Pontederia crassipes*?

The 37 articles attribute 43% to the use of its biomass which, in combination with other materials, generates a positive effect on the environment and the economy. A further 29% refer to efforts to reduce or better control the propagation of the aquatic plant in rivers and lakes due to the fact that it is a potential invader and 19% have demonstrated that *P. crassipes* is a potential source of alternative fuel. The remaining 9% of the studies correspond to specific research on the use of the plant in biocomposites, bioplastics, and bioethanol (Figure 4).

RQ3: Which are the countries where most studies on *P. crassipes* have been carried out?

The results of the analyzed sample revealed the countries in which *P. crassipes* study proposals have been made (Figure 5). In Indonesia, 24% of the studies were conducted, making it the country that has the most research on *P. crassipes* and proposing an improved economic impact in the region if used appropriately. Then, 19% of the studies have been carried out in Brazil, while Colombia and India represent 8% each. Argentina, Australia, and the Philippines account for 5% each of the papers. The remaining countries such as

Chile, Cuba, Egypt, United States, Italy, Kenya, Mexico, and Thailand represent 3%. On the other hand, at the University of the Armed Forces in Quito, Ecuador, studies were carried out on the proposal of four models of non-linear regression techniques corresponding to the biomass of *P. crassipes*, which would allow an experimental installation.

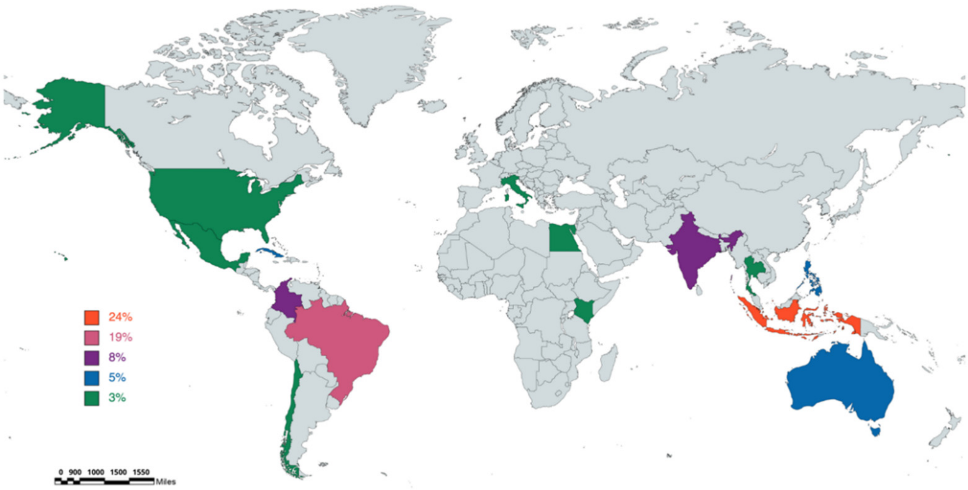

Figure 5. Main countries with studies concerning *P. crassipes*.

RQ4: What are the scientific studies in which *P. crassipes* has been used for the generation of biodegradables products?

Figure 6 shows that out of 37 studies, 49% are related to the manufacture of biodegradable products, where 80% are focused on the use of biomass. Furthermore, although there are different projects (fertilizer, methods, extraction, fuel, among others), they coincide in that the use of biomass has a high possibility of generating alternative products using its biomass. A further 10% corresponds to obtaining biocomposites, as investigated by [43] who analyzed the effect of biodegradation of *P. crassipes* in the manufacture of biocomposites, this being a specific process in order to optimize and improve the properties of biodegradable plastic [41]. Finally, 10% refers to the manufacture of bioplastics from *P. crassipes*, which proposes to improve the physical properties of the bioplastic starch by the addition of chitosan [42].

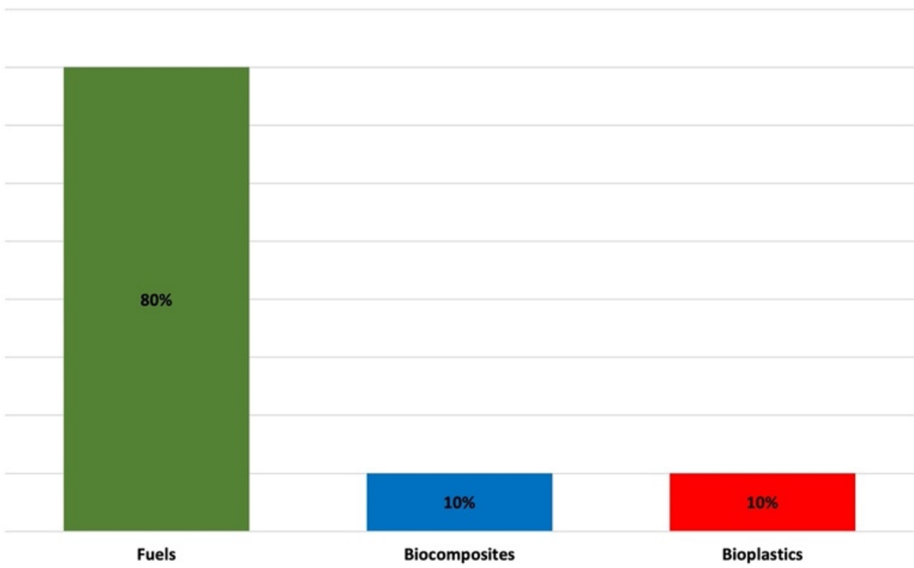

Figure 6. Articles on biodegradable products based on *P. crassipes*.

4. Conclusions

According to the research articles reviewed in this work on *Pontederia crassipes*, these plants are associated with various environmental aspects, mainly to contain its reproduction and propagation. However, the benefits attributed to it as a scientifically confirmed raw material have yet to be specified in tangible uses.

Studies on the use, control, and rapid reproduction capabilities of *Pontederia crassipes* do not address issues related to the production and commercialization of biodegradable products that could feasibly be a sustainable alternative for environmental conservation.

This review shows that only 19% of the research articles about *P. crassipes* which were addressed here propose it can be a potential source of alternative fuel. In addition, 9% of the articles are about specific research related to the use of the plant in biocomposites, bioplastic, and bioethanol.

From a production and commercialization perspective, it is necessary to do research on the creation of biodegradable products from the vegetal biomass of *Pontederia crassipes*. Moreover, it is important to study its use focusing on ethanol, bioplastics, eco-friendly paper, cattle fodder, fish food, bioremediation material for sewage water, cellulosic pulp, biogas, and organic fertilizer.

This review allows us to detect the need for further studies on the use of *P. crassipes* as a sustainable alternative, taking into account the potential to use of its plant material in the production and commercialization of products such as biodegradable packaging, handicrafts, pellets for aquaculture feed, nutritional blocks for cattle, building blocks, biopesticides, tea, and tinctures.

In the literature review, no evidence was found of its use as a raw material for the generation of alternative products (cardboard, pellets, packaging) using its plant biomass as the main source, despite the abundance of the species worldwide. Research and development opportunities were detected in the use of plant biomass to meet the global demand for plastics and other highly harmful compounds, which would allow contributing with another alternative solution for the integral use of *Pontederia crassipes*. On the other hand, it is essential to analyze the costs for obtaining homogeneous and standardized material of the compounds contained in *Pontederia crassipes*, which would help to make it a feasible option for its transformation into biodegradable products. Therefore, it is relevant to study the availability of *Pontederia crassipes* at the global, regional, and local levels, which supports the sustainable development of the regions where it is located and favors its use in order to subsequently promote the production of biodegradable products such as cardboard, pellets, packaging, and paper.

However, it will be necessary to analyze the supply and demand of bioplastics in the future, where *Pontederia crassipes*, due to its abundance, plays an important role. It is worth remembering also that it is possible to generate other types of bioproducts, for which a market study should be carried out; this will strengthen researchers and companies willing to direct their lines of research and development towards *Pontederia crassipes* as a source of raw material for products of vegetable origin and not only invest resources in trying to eradicate it.

In this way, a new line of research on *Pontederia crassipes* as a raw material to produce and market various biodegradable products, such as cardboard, paper, and packaging, which supports the mitigation of adverse effects on ecosystems, has been identified.

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

Appendix A

Table A1. Studies related to the use of *Pontederia crassipes* in propagation control.

Reference	Country of Origin	Use	Results
[27]	Australia	Propagation control	The geographic potential of *P. crassipes* is broad. Its extension towards the poles is limited by cold stress, and its ability to inhabit some tropical areas of Africa is limited by heat stress. Moreover, in some high altitude areas, it is too cold to persist. The overall impact of projected climate changes by 2080 on the potential distribution of *P. crassipes* in the Northern Hemisphere will be to allow it to expand its range northward as cold stress limits are exceeded. This pattern is most evident in North America, Europe, and northeastern China.
[31]	Brazil	Propagation control	The application efficiency and control efficiency of water hyacinth (*P. crassipes*) was evaluated with the use of diquat herbicide, conducted with two application volumes associated with three types of droplets. As a result, the use of extremely coarse and ultra coarse droplets is sufficient for the control of *P. crassipes*.
[44]	Chile	Propagation control	Of the 26 species of introduced aquatic plants growing in Chile, 14 were found to have invasive behavior in other parts of the world.
[30]	Argentina	Propagation control	In *P. crassipes*, in the decay period, leaves of smaller size have higher nitrogen content in the emissions compared to leaves of the growing period. The results show the importance of considering the combined action of these herbivores in the biological control of these aquatic plants.
[33]	Argentina	Propagation control	The results generated in this study can lead to scaling actions directed to the use of biomass for biofuel or fine chemical production.
[45]	Indonesia/Malaysia	Propagation control	Some invasive aquatic plant species were identified in Chenderoh and Jatiluhur reservoirs. Submerged and emergent species were found in shallow, continuously flowing reservoirs, while floating species were found on the surface of lakes and reservoirs. The special feature of phenotype plasticity means that plants can alter their growth form to adapt to current conditions.
[46]	Indonesia	Propagation control	Water hyacinth powder is made at the pre-hydrolysis stage with the aim of accelerating the process of separating the hemicellulose it contains.
[29]	Australia	Propagation control	In the Boolgooroo region, the Mungalla Wetlands, east of Ingham in north Queensland, weed abundance and water quality appear to oscillate, depending on summer rainfall, as changes in hydraulic pressure stop or allow sea to enter. A passive remediation method, such as reintroducing tidal flow by removing an earthen embankment or dike, could provide a more cost-effective and sustainable means of controlling freshwater weeds and improving shoreline water quality in the future.
[32]	United States	Propagation control	Six aqueous extractions were tested against 100 bacterial strains isolated from plants and soil to evaluate their activity. Harvesting these weeds and converting them into usable compounds could not only eliminate water quality and agricultural waterway problems in situ, but could also result in the development of new soil amendments or biopesticides.
[47]	Indonesia	Propagation control	The effect of leaf surface character on the ability of water hyacinth (*Pontederia crassipes*) to transpire water was evaluated. Based on the results of the study, it was found that lower leaf surface area is correlated with the number of stomata and transpiration rates in individual plants measured.
[28]	Brazil	Propagation control	*P. crassipes* from the Amazon floodplains was used to evaluate the effects of the combination of temperature and increased CO_2 on growth, physiology, and ecological interactions. *P. crassipes* experienced no mortality or change in any of the variables measured over the same period. The temperature-neutrality interaction shifted to ease for *P. crassipes*. Global climate change may alter the composition, biomass, and ecological interactions of Amazonian aquatic plant species.

Table A2. Studies related to the use of *Pontederia crassipes* as biomass.

Reference	Country of Origin	Use	Results
[13]	Egypt	Biomass/water treatment	The results indicated that reverse titration showed a revolutionary ability to detect, for the first time, different types of metal complexation present at equilibrium in aqueous extracts of biological samples. Moreover, the presence of *P. crassipes* in the Nile water is very useful to transform free Cu ions into less toxic forms by organic complexation.
[36]	India	Biomass/Fuel	Reducing sugar and glucose yields from enzymatic hydrolysis were maximal at high temperature and acid pH of substrate and enzyme load. Water hyacinth is also a potential biomass resource available in many tropical regions of the world and with proper technical knowledge, can be used as a feedback for small-scale distributed production of fuel ethanol.
[48]	Indonesia	Biomass	This process involved the conversion of the pentosan fraction in water hyacinth into pentose, and then the pentose was dehydrated into furfural. The furfural was identified by the Fehling's test, which was then characterized using Fourier transform infrared and proton nuclear magnetic resonance, followed by gas chromatography with mass spectroscopy.
[17]	Indonesia	Biomass	*Pontederia crassipes* and *Hydrilla verticillata* were recommended for combustion energy production. In general, the energy potential (calorific values) of the aquatic plants investigated was at a lower level compared to other types of biomass.
[37]	Colombia	Biomass	There is a positive correlation between the amount of metal removed and the contact time with the plant biomass, i.e., as the exposure time increases, the amount of metal removed increases. The results obtained with the Langmuir model indicate that the biomasses of stems and leaves of *P. crassipes* have a homogeneous surface with a specific number of active sites that, when saturated, inhibit the adsorption process of lead in solution.
[49]	India	Biomass	The study succeeded in producing hydrogen gas from aquatic weed pretreated with *P. crassipes* by anaerobic fermentation. Of the twelve bacteria isolated from different wastewater sources, ten strains had the potential to produce hydrogen under anaerobic conditions. Therefore, they were selected for anaerobic experiments with *P. crassipes* pretreated with acid and alkali. The results of the experimental analysis show that the alkali treated substrate produced a higher amount of hydrogen than the acid treated substrates.
[18]	India	Biomass	The adsorption of Congo red (CR) from aqueous solution onto burned root of *P. crassipes* biomass was investigated. A series of batch experiments were conducted using biomass to remove dye from aqueous systems. *P. crassipes* could remove up to 94.35% of CR from wastewater.
[38]	Brasil	Biomass/Fuel	In this work, three invasive aquatic plants were evaluated as feedstock to study the biooil production capacity, identifying the production of compounds including acids, sugars, alcohol, phenols, and other derivatives. The results generated in this study may lead to scale-up actions aimed at using the biomass for biofuel or fine chemical production.
[35]	Italia	Biomass	The water hyacinth is characterized by a high content of lignocellulosic biomass, with a medium lignin content, useful in both thermochemical and biochemical processes. In this work, a detailed analysis of the energetic properties of the water hyacinth biomass was carried out. This, in terms of its use in anaerobic digestion processes, before and after specific treatments, highlighting the improvements that the literature should make in the procedures.
[50]	N/A	Biomass	The bibliographic study of previous research works was performed, linked to the mathematical modeling of these facilities by the different techniques reflected in the specialized literature. A 3N experimental plan with three replications was carried out, from which four models corresponding to respective performance indicators were elaborated using neural network techniques, with satisfactory results of their evaluation based on regression coefficients and standard errors using *Pontederia crassipes* as biomass.
[51]	Brazil	Biomass	The response of the biomass of aquatic macrophytes under limnological changes after water level fluctuation in two tropical reservoirs was evaluated, these located in northeastern Brazil. The abundant and/or dominant species pre-WLF (water-level fluctuation) *Pistia stratiotes*, *P. crassipes* reduced their biomass post-WLF and correlated with temperature, total phosphorus, and nitrate. Reduced biomass of *P. crassipes* and *S. auriculata* in post-WLF expanded resource availability, allowing species coexistence.
[39]	Brazil	Biomass	The behavior of ceramics incorporated with fuel residues (*Pontederia crassipes* dry biomass) and flux residues (granite), as well as mixtures of both residues, was studied. The technological properties tested were dry bulk density, linear shrinkage, water absorption and flexural strength. The results indicate that the high calorific value of biomass residues represents a great energy saving possibility for the firing process. The embodiments can be indicated as a possibility of correct destination of the investigated residues.
[52]	Thailand	Biomass	TEMPO-oxidized cellulose nanofibrils (CNFs) with widths of 20 nm and lengths up to several micrometers were successfully prepared from water hyacinth with the help of mild mechanical disintegration. The TEMPO-mediated oxidation process was suitable for purifying the fibers without introduction of pretreatment steps. With the conversion of C6 hydroxyl groups to sodium carboxylate groups, sodium carboxylate, a significant decrease in the thermal degradation temperature of TEMPO-oxidized CNFs was observed.

Table A2. *Cont.*

Reference	Country of Origin	Use	Results
[53]	Brazil	Biomass	Biological and growth conditions of *Messastrum gracile* were evaluated to compare the effect of photoautotrophic and mixotrophic culture on increased biomass production and chemical conditions grown in macrophytic and commercial culture media. The growth rate for *P. crassipes* and culture media were higher in photoautotrophic culture. Protein contents were below the biomass dry weight in the photoautotrophic culture and below the biomass dry weight in the mixotrophic culture. *Messastrum gracile* grown in macrophyte culture media (*P. crassipes* and *L. minor*) and NPK (nitrogen, phosphorus, and potassium) culture medium provided satisfactory results with respect to lipid and protein contents in mixotrophic and photoautotrophic cultures, respectively.
[54]	Mexico	Biomass	In this study, it was demonstrated that biochar from *Pontederia crassipes* can be an amendment in acidic mining residues. It increased root length and reduced soluble copper and zinc to the same level as the other amendments in the waste substrates. The reduction of soluble Pb (lead) was lower with biochar than with lime in the mixtures and mining residues.
[55]	Brazil	Biomass	Elemental analysis showed that the nitrogen content of the fertilizer (FERT) was about 20%. Swelling tests demonstrated the effectiveness of the water hyacinth crosslinker, which reduced the water permeability of the material. The results demonstrated the promising ability of FERT to reduce nitrogen losses, as well as to minimize environmental impacts on the soil-plant-atmosphere system and improve the efficiency of nitrogen fertilization.

Table A3. Studies related to the use of *Pontederia crassipes* as fuel.

Reference	Country of Origin	Use	Results
[11]	Philippines	Biofuel	The potential of converting water hyacinth to charcoal briquettes with molasses as a binder was investigated in this study. The results demonstrated the potential of converting water hyacinth into an alternative fuel source.
[19]	Indonesia	Fuel	Water hyacinth is one of the alternative agricultural residues that can be used for biogas because a high hemicellulose F/M (food to microorganism) ratio can have an effect on biogas production.
[20]	Philippines	Fuel	Plant microbial fuel cells (PMFCs) are an emerging renewable energy source that can utilize wasted organic matter to produce electricity. The objective of this study was to determine the effect of combining PMFC technology with nickel phytoremediation. It is recommended to replicate and test the positive results of this study with other plants and heavy metals to establish a new hybrid process of bioelectricity generation and phytoremediation.
[21]	Indonesia	Fuel	The results indicated that the chemical elements of water hyacinth revealed dominant elements, i.e., oxygen and carbon. Since the biomass of water hyacinth has a relatively high volatile content and low calorific value, it is reasonable that water hyacinth can adequately in combustion with charcoal increase the reactivity of charcoal during the combustion process.
[34]	Kenya	Fuel	Local people were interviewed to obtain perceptions on the current and potential uses of water hyacinth, *P. crassipes*, growing in the Lake Victoria, in Kenya. From the findings, it was concluded that because water hyacinth grows widely in this region, there is an opportunity to expand biomass for bioenergy in the region. The results are expected to inform environmental and energy planning and decisions, particularly with respect to the negative impacts of water hyacinth and its potential values, source of organic fertilizer for crop production, handcrafts, etc.
[40]	Colombia	Fuel	The integrated design of this work consists of a phytoremediation process using *Pontederia crassipes* (live and dead), a biofuel production process composed of the hydrolysis bioreactor together with bioreactors for bioethanol and biohydrogen production. It is feasible to create and build a large-scale bioethanol and biohydrogen production system from *P. crassipes* biomass (loaded or not with heavy metals) that does not waste the biomass of this plant as is currently the case.
[56]	Cuba	Fuel	The application of nonlinear regression models of energy parameters to the specific case of the performance of downdraft gasifiers for *P. crassipes* biomasses. Individual models are obtained for each performance indicator of the operation such as the efficiency of the installation, temperature of the pyrolysis zone, calorific value of the syngas, and mass flow rate.
[43]	Colombia	Bioethanol	Four pretreatments (*Pontederia crassipes*) were evaluated for their transformation into sugars and ethanol. The dilute acid and alkaline delignification pretreatments were selected to be used in greater depth through the application of an experimental design, obtaining ethanol yield from dry biomass fed to the dilute acid pretreatment and dry biomass fed to the alkaline delignification pretreatment from the solid fraction.

Table A4. Studies related to the utilization of *Pontederia crassipes* as bioplastic and biocomposites.

Reference	Country of Origin	Use	Results
[41]	Indonesia	Biocomposites	A biocomposite comprising water hyacinth (*Pontederia crassipes*) nanocellulose and bengkuang starch was successfully fabricated using the solution casting method.
[42]	Indonesia	Bioplastic	Water hyacinth cellulose was successfully isolated by bleaching method followed by alkalization at low temperatures with maximum yield. In addition, bioplastic synthesis was successfully carried out by formulating starch and cellulose isolated under various compositions by adding chitosan and glycerol. The bioplastic prepared using starch showed better performance, such as higher strength, and degraded more easily compared to the other bioplastics prepared under different conditions, including starch bioplastic without added cellulose. The developed method presented is considered as a potential way to isolate cellulose from plants and use it as a reinforcing component in the production of bioplastics.

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