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Review

Eradication or Exploitation? Water Hyacinth Control Alternatives in Mexico: A Review

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Abstract

A systematic review of the scientific literature focused on the analysis of the main strategies related to the management of *Eichhornia crassipes* [water hyacinth] in Mexico is presented. The review was classified according to the levels of the biomass valorization pyramid, using specific inclusion and exclusion criteria: (i) eradication; (ii) physical control of the plant; and (iii) exploitation of its biomass. It focused on research conducted in Mexico from 1971 to 2023, which allowed for the analysis of a total of 147 studies. The results indicated that 73.4% of the research in Mexico is oriented towards the exploitation and valorization of water hyacinth biomass through the transformation of the plant into mid-value products, such as chemicals and materials (70.7%), energy (12.2%), food (7.3%) and health and lifestyle products (9.8%); however the sectors considered high-added-value, such as pharmaceuticals, fine chemicals and food, continue to be areas of opportunity. The remaining 26.6% focuses on control and eradication strategies, through the insertion of biological enemies, and physical control, by means of cutting and crushing the plant in situ. This situation underscores the importance of promoting integrated management approaches that incorporate biomass recovery, contributing to environmental sustainability and the responsible use of this invasive resource.

Keywords: biomass valorization; control alternatives; environmental sustainability; water hyacinth

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1. Introduction

Lake ecosystems are vital for the full development of human well-being due to their capacity to provide various essential and valuable ecosystem services for life and society [1], which include recreation and tourism, the provision of habitat for diverse species and fertile soils, the supply and control of water quality, nutrient regulation services, climate, groundwater recharge, carbon sequestration, food supply, and boosting the economic sector [2–5]. However, these ecosystems' functioning is currently disrupted due to various problems, such as climate change, acidification, eutrophication, intensified land use, exacerbated resource extraction, and biological invasion [6,7].

Among the various forms of biological invasion, a type of species known as invasive, which typically has a defined distribution and abundance in countries or regions beyond its origin, can reproduce abundantly in the sites where they are introduced, causing imbalances in the state of the invaded areas and ecosystems, damage such as the displacement and loss of local species and a deterioration or change in ecosystem functions, and other negative impacts [8,9]. Aquatic plant invasion is a common type of biological invasion around the world [10]. The unique attributes of aquatic invasive plants allow them to become widely distributed in water bodies, producing radical alterations in the processes of aquatic ecosystems, changing their environmental conditions, and causing modifications in the endemic biological diversity, which has socio-economic and human health repercussions in the local–regional society [8,11].

Mexico is a federal republic composed of 32 federal entities (states), with extensive river basins, reservoirs, lakes, and irrigation districts that sustain key economic activities and regional livelihoods [12]. In 2023, the agricultural sector accounted for 32.2% of the total water extraction, while industry used 12.2%, highlighting the strong dependence of productive systems on freshwater availability. In parallel, the economic costs associated with groundwater depletion and surface-water degradation have been estimated at 102,029.4 million pesos (0.32% of GDP), underscoring the persistent environmental pressures on national water bodies [13]. Within this context, aquatic invasive plants can intensify operational and socio-economic impacts by blocking canals and water intakes and by limiting navigation and productive uses of water bodies [14]. In Mexico, 665 species of invasive exotic plants have been identified [15], among which water hyacinth (*Eichhornia crassipes [Mart.] Solms*) stands out due to its high proliferation rate in many national aquatic bodies [16]. *E. crassipes* is a hydrophytic aquatic plant belonging to the *Pontederiaceae* family, which generally grows in bodies of fresh water. More than 50% of its biomass is made up of amorphous and fibrous submerged roots, which float freely and can reach 50 cm or even 1 m high in very favorable tropical conditions [17]. It is native to South America, specifically the Amazon Basin of Brazil, and has spread accidentally and been spread deliberately throughout the tropics and subtropics and in many warm temperate zones to more than 50 countries worldwide [18]. Invasions have been reported in Asia, Africa, Europe, the Caribbean, North America, and Central America [19].

It is estimated that water hyacinth entered Mexico more than 100 years ago through anthropogenic activities [20]. This exacerbated its spread, with it covering approximately 70,000 hectares of surface [21–23]; it is distributed to a greater extent in the central area of Mexico, being dispersed along the Pacific slope, from Sinaloa to the South and on the Gulf of Mexico slope, from Tamaulipas to the Yucatan Peninsula, and in the subtropical and temperate zones of the hydrological basins of the Bravo, Balsas, Panuco, and Lerma-Chapala-Santiago rivers [24]. Today, *E. crassipes* is the non-native species most observed in the country's continental waters [20].

Water hyacinth is considered one of the worst aquatic weeds due characteristics such as its rapid ability to form floating and intertwined mats on the surface of bodies of water, its complex root structure, and its rapid reproduction rate [25,26]. It presents sexual reproduction (its seeds have a lifespan of up to 20 years) and asexual vegetative reproduction by stolons, which has allowed it to achieve annual reproduction rates above 1400 tons per hectare, thus achieving its peculiar invasive success [27,28].

Additionally, *E. crassipes* is a very adaptable species to environmental conditions, capable of tolerating wide variations in the concentration of nutrients in the aquatic body where it resides, as well as different pH and temperature levels [29]. The optimal environmental conditions for its development are in the following ranges: pH between 6 and 8, with an

optimal temperature of 25–27.5 °C and high concentrations of nitrogen. It shows sensitivity to temperatures below 1 °C and above 33 °C, which generally reduce its reproduction rate [30,31]. Also, with sufficient available space, the species can expand horizontally to produce new generations, maximizing the use of light and nutrients. On the other hand, if the available space is limited, *E. crassipes* tends to grow vertically, accumulating energy and nutrients for better development and sexual reproduction [32].

The success of water hyacinth as an invasive plant is due to its ability to compete with phytoplankton and native vegetation and the absence of consumers of this plant in the areas in which it has been introduced [33]. It is important to note that when this aquatic plant proliferates in a body of water, it causes a drastic change in the ecosystem, often leading to environmental degradation and loss of biodiversity [34], because it can modify the physicochemical characteristics of aquatic bodies, producing eutrophication and evapotranspiration and causing severe problems in rivers, reservoirs, and dams [35]. This species is capable of absorbing large quantities of water, which then is evaporated into the atmosphere; also, the plant reduces the amount of dissolved oxygen by preventing the transfer of air to the surface of the water, preventing the passage of light, which causes alterations in the adequate growth of aquatic flora and fauna in the freshwater bodies they invade [36,37].

Regarding the damage caused to society and human health, water hyacinth infestations are associated with infection centers due to water stagnation and waste accumulation, forming a suitable habitat for the development of disease vector organisms—for example, mosquitoes such as *Anopheles* sp. and *Mansoria* sp., which transmit malaria and encephalitis, respectively, among others [38,39]. In addition, water hyacinths are highly complex to eradicate once they have become established in the water body. Hence, the main goals of most management efforts are to reduce the economic costs and ecological impact through their control [40].

Conventional methods currently used for *E. crassipes* control worldwide are grouped into three main groups: physical (manual or mechanical removal), chemical, and biological control methods [41]. Global experience indicates that sustained control is most often achieved through integrated management rather than a single intervention, combining mechanical removal, targeted chemical control and classical biological control. In this context, host-specific biological control agents, especially the weevils *Neochetina eichhorniae* and *N. bruchi*, have been widely implemented and are frequently reported as key contributors to long-term suppression under appropriate environmental conditions [42–44]. Large-scale experiences support these observations; for example, the decline in water hyacinth in Lake Victoria was attributed primarily to widespread damage by *Neochetina* spp., with climatic/hydrodynamic conditions acting synergistically [45]. Similarly, in South Africa, long-running national biological control initiatives have combined the establishment of multiple natural enemies with complementary measures when required, emphasizing adaptive management and reinfestation control [46]. In the United States, institutional programs (e.g., Florida's statewide aquatic plant management) and federal frameworks (USACE Aquatic Plant Control Program) apply planned combinations of removal and control actions to protect navigation and other water uses [47,48].

However, each control method has to be adapted to all situations and needs, generating contextual and specific management strategies for each invaded site [49]. For this reason, water hyacinth management is one of the biggest challenges in the field of invasion biology. Currently, Mexico is focused on the eradication of the plant through the method of physical control, which is considered the best short-term method for weed control in small areas [16], using mechanical removal with machinery (land buckets, dredges and

water-based machinery; harvesters and barges), and barriers or fences for manual containment and removal [41,50]. Specifically, manual removal consists of the organization of brigades of villagers to manually collect water hyacinth with the help of crushers and other instruments [51]. However, another approach to the management of water hyacinth has emerged, which is based on the use of its biomass as raw material.

At a global level, water hyacinth research has been considerably addressed in reviews, which have emphasized the environmental services provided by the plant, such as phytoremediation, and the various applications and use of biomass from the plant for energy generation and high-value bio-products in the market, such as biochar, compost, bioethanol, biogas and animal feed [19,49,52,53]; nevertheless, the eradication methodologies and control have been little addressed and the information is still very dispersed, despite this being the approach that is most commonly used for the control of the plant.

In this sense, the objective of this work was to carry out a systematic review of the literature in the Mexican context from 1971 to 2023, integrating two complementary perspectives: the eradication and control of *Eichhornia crassipes* as an invasive species, and its utilization for bioenergy and bioproducts classified and assessed within the biomass valorization pyramid [54], in order to identify sustainable management pathways. Unlike broader global reviews, which tend to present generalized conclusions, this study offers a Mexico-specific, pyramid-based synthesis that consistently organizes the evidence across management and valorization routes, while also providing a temporal and geographic reading of national research trends to better reflect local trajectories, implementation constraints, and policy-relevant needs.

Ther article is organized as follows: Section 1 introduces the background, context and relevance of *Eichhornia crassipes* in Mexico; Section 2 describes the methodology and the criteria applied for the systematic review, Section 3 presents and discusses the results, divided into two subsections corresponding to each perspective, and Section 4 provides the main conclusions and perspectives derived from this review.

2. Materials and Methods

A systematic review of the literature can be explained as a research method and process whose purpose is to identify and critically evaluate relevant information, as well as to collect and analyze the data from such research [55], in order to identify all the empirical evidence that fits the defined inclusion criteria to answer a particular research hypothesis or question [56]. A systematic review of the literature avoids potential biases and provides reliable results, from which conclusions can be drawn and decisions made [57].

For this paper, a systematic review of the literature was carried out using, as an analytical framework, the guidelines established in PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) [58] (see PRISMA 2020 checklist in the Supplementary Materials). This review has the following stages: (1) revision design, (2) conduct of the review, (3) information analysis, and (4) the results and drafting of the review.

2.1. Revision Design

2.1.1. Objectives of the Review and/or Background

Water hyacinth infestation is a major problem worldwide, which generates a strong need for more knowledge and scientific information related to this plant. This review was conducted to systematically analyze the literature on water hyacinth studies in Mexico from 1971 to 2023, integrating perspectives on both the use and exploitation of its biomass

for bio-product generation—classified and valued within the biomass valorization pyramid [54,59]—and those focused on its eradication efforts, as well as those aiming to identify opportunities for its sustainable management as a consistent and regular biomass source, while addressing the challenges associated with its infestation.

2.1.2. Research Questions

As a first step in the review design stage, the research questions to be addressed were defined, aligning with the eradication (E) and uses or exploitation (U) of water hyacinth, which are presented as follows: (E-1) What methods and strategies have been implemented in Mexico for water hyacinth eradication? (E-2) What control methods are currently used? (E-3) In which states of Mexico have been conducted studies focused on water hyacinth eradication? (U-1) How is water hyacinth biomass utilized in Mexico? (U-2) How can its applications and derived bio-based products be systematically classified within the biomass valorization pyramid? (U-3) Which states in Mexico have extracted water hyacinth for valorization purposes? (U-4) What are the predominant uses within the biomass valorization pyramid? A general question was also presented: what is the focus of *E. crassipes* research in Mexico?

2.1.3. Research Strategies

Once the research questions were identified and considered, the review approach was developed, focusing on the search strategy for the identification of the relevant literature in the selected research databases. Then, the inclusion and exclusion criteria were defined.

2.1.4. Inclusion and Exclusion Criteria

The first inclusion criteria were used to select reports using the following search keys: lirio acuático + Mexico, water hyacinth + Mexico and *Eichhornia crassipes* + Mexico. Likewise, the second inclusion criterion considered the literature that specifically addressed the utilization of *Eichhornia crassipes* as raw material, either for processing into bio-products or for direct use without transformation, as well as studies focused on its eradication. Regarding the exclusion criteria, the first was studies carried out outside Mexico, and the second one considered the literature where *Eichhornia crassipes* was taken as an example, but was not the central theme of the study. In addition, we applied no restrictions regarding publication type or language. Peer-reviewed articles and the gray literature (e.g., theses and technical/government reports) were screened using the same inclusion and exclusion criteria, with no differential weighting in the qualitative synthesis. Document type was recorded for descriptive purposes only. Searches used Spanish and English keywords, and studies in either language were eligible.

2.2. Review Outline

Information was sought through selected scientific research databases, which included Science Direct, Scopus, Springer, Dialnet, Scielo and Google Scholar. The review was conducted over a time interval from 1971 to 2023. Despite efforts to carry out an exhaustive review, we found, as a limitation, that not all the literature was available due to requirements for paid access. Additionally, some of the literature was omitted because it was not linked to the search keywords.

2.3. Information Matrix

For the standardized data extraction, a database was developed, including the following information: (1) consecutive number, (2) year, (3) title of the study, (4) reference,

(5) institution, (6) state, (7) municipality, (8) name of water body, (9) type of report, and (10) purpose of the study.

2.4. Quality Appraisal/Risk of Bias

Given the heterogeneity of the sources included (peer-reviewed articles and gray literature such as theses and technical/government reports), a single risk-of-bias tool designed for clinical studies was not applicable. Instead, each included document was appraised using a simple and consistent set of reporting-quality criteria: (i) clarity of objectives and scope; (ii) transparency of methods (e.g., description of the control/valorization approach and, when relevant, operational/sampling conditions); (iii) presence of traceable results (quantitative or clearly documented qualitative outcomes); and (iv) consistency between methods and conclusions. This appraisal was used for descriptive purposes and to support the interpretation of the results, and observations were recorded alongside the extracted information in the information matrix. Studies were selected exclusively using the eligibility criteria described in Section 2.1.4.

2.5. Software Used to Create Maps, Diagrams, and Graphs

All visual materials included in this manuscript [maps, diagrams, and graphs] are original and were newly created by the authors specifically for this study. The maps were produced using Adobe Photoshop CS6 (v13.0) in conjunction with Adobe InDesign CS6 (v13.0) [60,61], where they were generated and prepared in a publication-ready format, including carto-graphic design, the composition and organization of visual elements, text and label adjust-ments, and the standardization of the graphical presentation to maintain consistency throughout the manuscript. The use of Adobe Photoshop CS6 and Adobe InDesign CS6 required a software license. Conceptual diagrams and composite figures were designed in Canva [62], a web-based design and layout platform available in both subscription- based and non-subscription modalities; in this study, we used the non-subscription (free- access) modality. Graphs were generated in Microsoft Excel [63] based on the curated dataset extracted during the literature review and exported for integration into the final figures.

2.6. Revision Highlights—Statistical Information

Research was classified according to the number of publications per year, as well as the research approach regarding water hyacinth. Specifically, the studies were categorized according to whether they focused on the direct use of the biomass or its utilization through a conversion process in which water hyacinth serves as a raw material, or if they were focused on eradication for control purposes. Additionally, a categorization was made concerning the different uses of the plants, emphasizing bio-product production, which was classified and valued within the biomass recovery pyramid. Finally, the states of the Mexican Republic with the highest incidence of extraction for productive use were identified, as well as those where studies were conducted focusing on plant eradication.

As shown in Figure 1, a total of 3893 records were identified in the databases using the keyword combinations lirio acuático + Mexico, water hyacinth + Mexico and *Eichhornia crassipes* + Mexico, of which 778 corresponded to duplicate records; therefore, 3115 single records were evaluated by title and summary. Of these, 2968 were excluded for not meeting the previously established inclusion criteria.

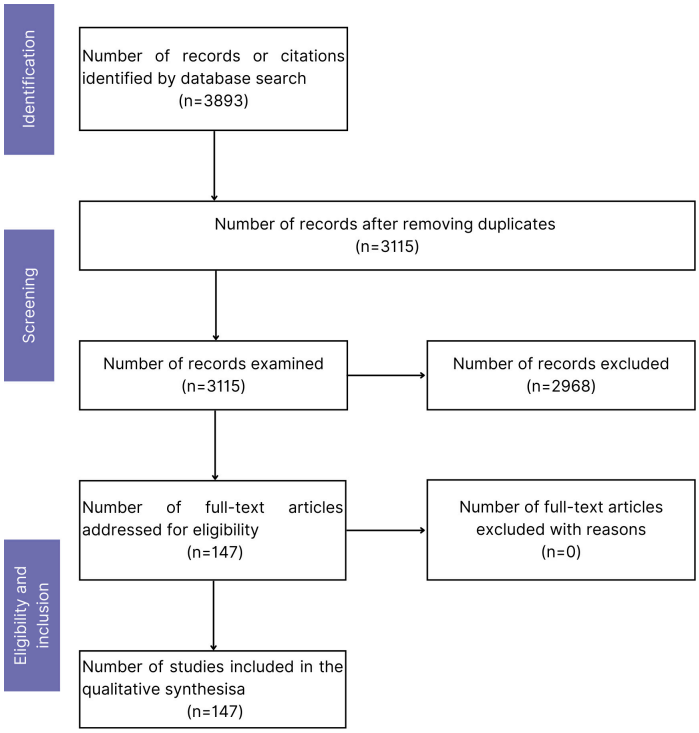

Figure 1. Outline of the methodological process followed for the identification, refinement, evaluation and inclusion of studies in the systematic review.

3. Results and Discussion

A total of 147 studies were included in the qualitative synthesis, of which 109 focused on biomass use and utilization, while a total of 38 studies focused on efforts to control and eradicate the plant. Figure 2a shows the trends in the approach to *Eichhornia crassipes* research in the Mexican context. An increase can be observed in the number of investigations of water hyacinth over time; during the years 2016, 2017 and 2022, the largest number of studies was published. Responding to the general question regarding the focus of *Eichhornia crassipes* research in Mexico, Figure 2b indicates that research on water hyacinth in Mexico is mainly oriented towards its direct use or its utilization through a conversion process in which it serves as raw material, while, to a lesser extent, we also found approaches focused on its eradication; these focuses made up 73.4% and 26.6% of the total, respectively.

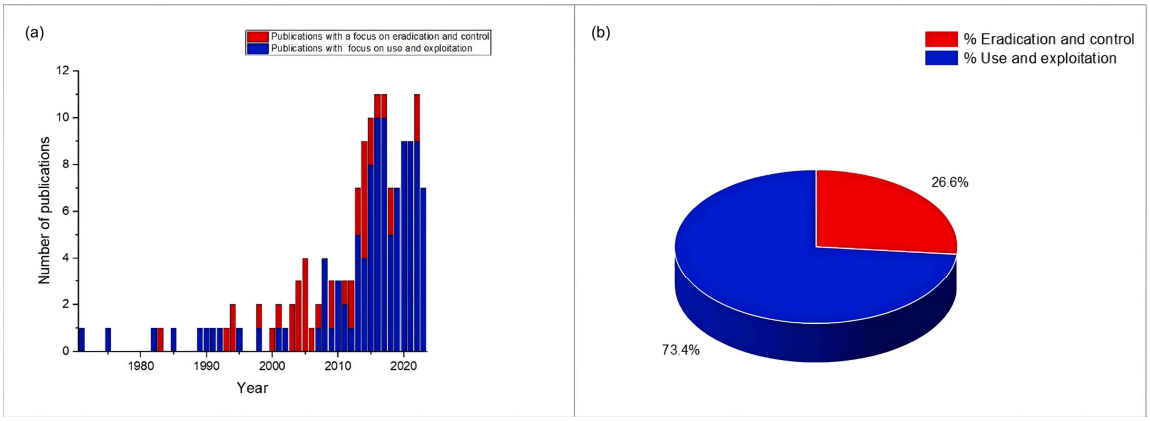

Figure 2. (**a**) Number of publications on water hyacinth in the Mexican context. (**b**) Orientation of water hyacinth research in Mexico.

3.1. Studies on Water Hyacinth Eradication and Control in Mexico

In Mexico, the published literature reports on water hyacinth control programs tested across different aquatic bodies and their effectiveness in managing the specie's proliferation. Few studies have been carried out addressing the eradication of water hyacinth, despite this being the approach most commonly used in Mexico for the control of the aquatic species. It is important to note that the studies reported for this type of approach emanate from socio-environmental and governmental programs, whose main objective is the preservation and environmental restoration, seeking ecological balance, the restoration of environmental services, and other issues involved in the security and rational use of lake ecosystems, using socio-ecomanagement action models and landscape recovery methodologies [64,65]. A considerable portion of these studies described experiences adapted for different regions in the country; however, an analysis of such experiences with the aim of identifying an adequate control strategy is lacking.

As mentioned above, water hyacinth is an invasive plant species causing damage to freshwater ecosystems, such as loss of water through evapotranspiration and the deterioration of water quality, and damage to biodiversity, specifically to the native species of the region [66], as well as causing various economic problems due to the obstruction of canals and irrigation areas, restrictions on fishing and tourism activities, and health problems associated with infestation; thus, the implementation of various weed control programs is required.

Weed control can be defined as a reduction in population density to an acceptable number and loss of plant vigor per unit area of an aquatic plant population considered undesirable in a given water body [67]. Three techniques for plant reduction have been highlighted: physical, biological and chemical control. The first one consists of the direct extraction of the plant, either manually or mechanically through the implementation of heavy machinery such as harvesters or dredgers. Biological control involves the insertion of natural enemies of the invasive species, while chemical control involves the use and application of a wide variety of herbicides, such as glyphosate (isopropylamine salt of N-phosphomethylglycine), diquat (6,7-dihydrodipyridol pyrazinedione) and 2,4-D amine (2,4-dichlorophenoxyl), which are highly effective and economically viable, but produce harmful effects and alterations in the environment and water quality [68,69]. Finally, there is integrated control, which refers to a combination of these methods [16,70,71].

Chemical and mechanical control methods have been used in Mexico since 1958 for the management of water hyacinth [67]. However, in 1993 the Weed Control Program (PROCMA) was created, whose main goals included a reduction in weeds to manageable levels, the establishment of maintenance programs, the comprehensive management of weed control and the formulation of integrated wastewater management [72]. To support the actions and guidelines of the various control programs established in the various irrigation areas, it was first necessary to carry out experimental work on the various aquatic bodies in order to validate the most sustainable control methods [16].

The scope of research focusing on eradication and control involved studies published over a period of 29 years, from 1993 to 2022, is summarized in Figure 3. This shows the production of studies related to eradication methods as an alternative means of controlling water hyacinth in Mexico, from which is possible to observe that the highest number of studies were reported in 2014.

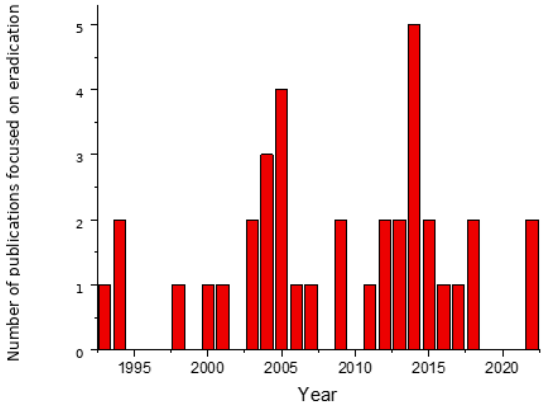

Figure 3. Number of publications focused on eradication in Mexico.

3.1.1. Geographical Distribution of Studies

In Mexican aquatic bodies where economic and social activities are carried out, the surface infestation by aquatic weeds is roughly 62,000 ha, with water hyacinth being the main weed, affecting 64% of the infested surface [73]; also, this species is widely distributed in the Mexican Republic, especially in the central area, on the Pacific slope, from Sinaloa to the south, and on the Gulf slope, from Tamaulipas, to the Yucatán peninsula, in the temperate and subtropical zones of the hydrological basins of the rivers Lerma—Chapala—Santiago, Balsas, Pánuco and Bravo. However, based on the literature review process, it was only possible to identify a total of 10 states in the Mexican Republic and Mexico City where water hyacinth eradication methods have been implemented and reported. Importantly, only 29 out of the 38 eradication/control studies reported the specific (states) where extraction works were implemented; therefore, the percentages shown in Figure 4 are based on these 29 studies. As shown, Sinaloa state hosts most of the aquatic bodies where the largest number of water hyacinth eradication works have been carried out, with 17.24%; in second place is Mexico City, with 13.79%; then Hidalgo, Jalisco and Puebla with 10.34%; and Guanajuato, Michoacán, Morelos, Nayarit and Veracruz with 6.9%; and finally Sonora represents 3.45%.

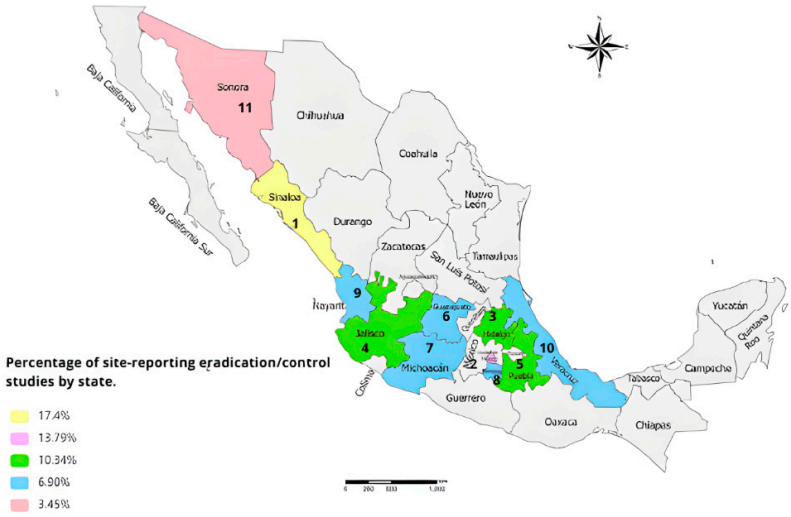

Figure 4. Map of areas with water bodies where hyacinth control methods were used, Mexico. Colors indicate the percentage of eradication/control studies that reported the state in which field actions were implemented (total number of data = 29): 17.24% (5 studies), 13.79% (4), 10.34% (3), 6.90% (2), and 3.45% (1). Numbered states: (1) Sinaloa; (2) Mexico City; (3) Hidalgo; (4) Jalisco; (5) Puebla; (6) Guanajuato; (7) Michoacán; (8) Morelos; (9) Nayarit; (10) Veracruz; (11) Sonora.

3.1.2. Control Methods

In Mexico, more than 40,000 hectares of reservoirs, canals, drains and lakes are affected by infestation with *Eichornnia crassipes* [74]. Since 1950, various control methodologies have been implemented, including physical, biological and chemical control; however, these methodologies have only provided temporary and highly expensive controls [75]. For this reason, the creation of PROCMA in 1993 sought to improve these methodologies, implementing them in a comprehensive manner [73]. However, efforts to control this weed have been considered as "individualists", which means that a local government, users or the affected population controlled it in individual water bodies; therefore, enhancing isolated control efforts is considered a priority [76].

Based on the reported experiences with the different control methods, it was identified that each method has limitations, which affect its proper management and effectiveness; some of the main variables involved in the control methods are the infestation area, the degree of maturity of the mat, the distribution of the plant, the presence of native species, especially if they are in danger of extinction, the anthropological activities carried out in the body of water, and the longevity of the germination of the seeds, as well as other factors, such as climate, temperature, light density and the amount of organic matter [66].

Physical Control of Water Hyacinth

Physical control is defined as the use of physical devices to destroy the species in situ or as transport mechanisms to disposal sites for weeds [72]. This type of control includes the manual method and the mechanical method. It is important to note that the method of physical extraction is the only one that allows for the sustainable use of water hyacinth, for instance, the conversion of extracted biomass into high-value products. The application of physical methods allows for the collection of the raw material and enhances its valorization towards a wide range of bio-products; this method could be considered the most appropriate due to the elimination of the weeds, generating economic and social benefits.

The manual method consists of removing the plant in situ by labor using hand tools such as scythes, sickles, rakes and cranks, and must be carried out with appropriate safety equipment (boots, coveralls and safety cords). This technique is generally applied in small or shallow water bodies where machinery cannot operate efficiently. In some cases, manual removal has been implemented through citizen participation programs, which significantly reduce costs since the labor is provided voluntarily. It has been reported that, using this manual method, a single person is capable of extracting up to 2.5 tons of water hyacinth per day [77].

The mechanical control method consists of the removal of weeds by extraction and/or crushing using machinery such as weed cutters, harvesters, crushers and dredging machinery. The machinery can be divided into two large groups according to the functions performed: the first group aims to extract water hyacinth through cutting and shearing for subsequent transport and discharge out of the body of water; in the second, the goal of the machinery is to crush the water hyacinth and leave it suspended in the water. In areas with high conservation values and high ecosystem services, such as wetlands, mechanic removal is the most effective option for initially restoring waterway function, although its application has high costs. When the mats reach a degree of maturity, they are thick and heavy, hindering their removal; in such situations, physical elimination, specifically mechanical removal, is the most viable option since dredgers or harvesters will cut and shred the carpets, allowing for their removal and, therefore, the appearance of the water mirror. However, there are also cons to this method—for instance, during cutting and crushing processes in situ, some plants are not extracted from the body of water and simply

die and decompose in the water, decreasing the dissolved oxygen levels and catalyzing phosphorus release into sediment. This process accelerates eutrophication in the water body and increases the proliferation of water hyacinth [78].

In Mexico, the use of equipment and machinery in various water bodies has allowed for the control of weeds in an efficient and timely way, but with high associated costs [79]. Table 1 shows the experiences of the mechanical control of water hyacinth in Mexico over time. The country has 85 irrigation districts, which are distributed with the following hydrological infrastructure: 13,026 km of main canals and 35,717 km of secondary ones. Also, it has been reported that, on average, 35% of the budget for the conservation of irrigation districts has been used for the mechanical control of weeds [80]. Additionally, important concepts such as the theoretical optimization of the use of machinery in to determine the optimal machinery and the best time to replace them have been applied for mechanical control purposes [16].

These bases provide the opportunity to develop optimal control strategies, reduce operation and infrastructure maintenance costs, and avoid the deterioration of machines and improve the efficiency of services and delivery of water to the population. Research in development and innovation must be focused on the design of harvesters so that they operate under optimal conditions, to reduce cost and energy requirements [81]. Similarly, another action should emphasize monitoring programs to evaluate the effects after the mechanical control of water hyacinth, and to identify the environmental issues associated with the crushing and degradation of organic matter; however, this last action has not been realized [79], despite some reports indicating monitored changes in water quality and biological communities prior to and after the application of the physical control. The most important findings were identified as changes in the nutrients and the orthophosphate concentration for nitrate and nitrite, which increased by 320% and 450% respectively. Also, NH3 reached lethal values for at least four months after crushing, phytoplankton decreased, and fish disappeared after the crushing of weeds due to the increase in nutrient concentrations, which may be attributed to the release of nutrients during the decay of matter.

Biological Control

Biological control involves the use of host-specific natural enemies to reduce pest and weed population density. There are three types of basic strategies for the implementation of biological control programs: the first one is classic biological control, which involves the insertion of endemic natural enemies of the pest; the second one is biological control by increasing natural enemies, which consists of increasing the density and therefore the efficiency of existing natural enemies in order to increase their impact; and the last one is biological control through the conservation of natural enemies, in which cultural practices or modifications to the environment are carried out, helping to preserve and increase the efficiency of natural enemies [82]. Several insects, such as moths, weevils and fungi, have been described as being capable of controlling water hyacinth infestation. The most limiting factor of this control method is that it is considered a slow process, so it should be used as part of a comprehensive long-term strategic program to achieve good yields [83].

The species *Neochetina eichhorniae*, *Neochetina bruchi*, *Sameodes albiguttalis*, *Cornops aquaticum Bruner* and *Orthogalumna terebrantis*, also known as neoquetinos, are well-established in Mexico and have been used as biocontrol agents [84], gradually reducing the population of water hyacinth in various aquatic bodies in Mexico [16,73,83,85–88]. It is important to mention that during the first year of execution of this type of control, the insect is spread, while the second year is considered the "start of control", and the third and fourth years are considered the "effective control".

Specifically, biological control using the species *Neochetina eichhorniae* and *N. bruchi* in various irrigation districts in Mexico has kept water bodies free of infestation for more than 15 years, when massive releases were made, and it took only about 2 years for their proper establishment and explosive propagation [16,89].

It is important to mention that prior to mass releases, it was necessary to carry out experimental tests on demonstrative plots of 2 m^2, in which various insect and water hyacinth densities were evaluated and compared against control quadrants to study the development of water hyacinth without the presence of insects; these tests allowed for an evaluation of the efficiency of insects in different temperature ranges, levels of water quality and timings [16,86].

The control method for these species is given as follows: when plants reach maturity, insects feed on the aerial part of the plant, causing a reduction in the photosynthetic capacity and productivity of the plant, and leading to its death; however due to the high reproductive and adaptive rate of water hyacinth, the use of a single level of biotic stress may not be the most efficient to stop the growth and reproduction of the plant. Therefore, the joint use of biological control agents is a more viable option. Plant pathogens can be used as biological control agents due to their ability to inflict foliar diseases that weaken the plant, and their ease of dissemination and propagation are considered synergistic components to the effect caused by insects. Some of these pathogens include *Acremonium (Cephalosporium) zonatum (Saw.)*, *Alternaria eichhorniae*, *Cercospora piaropi*, *C. rodmanii*, *Myrothecium roridum* and *Uredo eichhorniae* [90]. The strains of the fungi *Cercospora piaropi* and *Acremonium zonatum* have shown efficacy in reducing water hyacinth, with toxins that cause fungi damage, affect the host cells and inhibit enzymatic reactions, which affects the development of the plant and the production of the toxin cercosporin (1,12(2-hydroxypropyl)-2,11-dimethoxy-4,9-dihydroxy-6,7methylenedioxyperilen-3,10-quinone). This causes damage to the cell membranes of host plants, producing electrolyte deficiency and cell death [84,91], making them the most prevalent and destructive pathogens. Montenegro-Calderón et al. [92] isolated fungal cultures with different morphologies from water hyacinth leaf spots, aiming to achieve biocontrol of the plant, using partial DNA sequences of nrRNA gens and five protein-encoded genes. According to their results they were able to identify the two native species belonging to the genus *Cercospora*, *Cercospora piaropi Tharp* and *C. rodmanii Conway*, with the latter being the most pathogenic and aggressive.

On the other hand, the use of herbivorous fish species, such as *Ctenopharyngodon Idella* (commonly known as grass carp), has been shown to be an effective biological control method for water hyacinth infestation. Specifically, it has been reported that a population of 2500 fish, with an average weight of 1.24 kg, can control up to 35 hectares of water hyacinth infestation mats in the absence of other vegetation [93].

Mohedano López [64] proposed a socio-ecomanagement action model in the Tecocomulco Lagoon to address landscape pollution caused by the infestation of water hyacinth. Among the measures included in the action plan was the implementation of a biological control strategy through the introduction of 72 pairs of neoquetinos of the species *Neochetina eichhorniae* and *Neochetina bruchi*. The initiative reported improvements in the visual quality of the aquatic landscape and raised community awareness regarding sustainable management practices. On the other hand, in the study of Aguilar Zepeda et al. [83] proposed and described the importance of monitoring the biological control method and the application periods, as well as the incorporation of knowledge regarding the transfer of technology and the estimated costs arising from biological control actions, in coordination with mechanical control processes. The authors recommended a minimum density of six insects per plant and releasing them progressively onto water hyacinth mats not subject to mechanical control. The study reported the favorable

adaptation and survival of *Neochetina bruchi* and *N. eichhorniae* populations in the Humaya Canal (Sinaloa), supporting the feasibility of integrated biological and mechanical control strategies in tropical irrigations systems. Camarena Medrano et al. [89] looked at the indirect monitoring of the number of insects through counting bite marks from neoquetinos on the leaves and their relationship with the insect density per plant; their quantification was made over an average period of 3 years, taking into account the average number of bites recorded on the third water hyacinth leaf (generally the most developed). They identified when there were more than 50 bites/leaves, the damage to the water hyacinth increased, which could be obtained with a density greater than one neoquetino adult/plant; also, the density increased rapidly, causing further damage to the plant and achieving more effective control, with a density of up to eight insects per plant. The information reported regarding the number of insects per plant provided an effective mechanism for the technicians and producers who carry out biological control to identify the progress of the method and provide an adequate follow-up. In this sense, so-called socio-ecomanagement action models have also been implemented in order to guarantee a high level of environmental protection. Mohedano López & Rico Martínez [65] simulated the breeding trajectory of water hyacinth by means of 2DCAvN complex systems, as part of an ecomanagement plan to safeguard the Laguna de Tecocomulco. The simulation yielded approximations of up to 90% according to what was reported, allowing them to maximize their control management.

The wide biological diversity of Mexico allows for the presence of a wide variety of insect species that can be considerable agents of infestation of aquatic weeds such as water hyacinth. The various success experiences reported by biological control by inserting species as neoquetinos indicate that this method could lead to excellent results, providing a potentially less harmful alternative for the environment; however, there are still a large number of control agents that lack research and evaluation, which provides a great opportunity for Mexico to launch comprehensive project initiatives with these agencies. It is also necessary to carry out a greater number of works at the experimental level that allow for findings regarding the insertion of biocontrol agents to be evaluated in order to be able to execute these plans on a large scale.

Chemical Control

Chemical control is based on the use of herbicides, which offer rapid action and effectiveness, depending on the application, as well as a monitoring consistency of up to 20 years [94]. However, in certain circumstances their use for control in areas with fish purposes is limited by the high chemical concentration, which is harmful to both the endemic plant and animal species in the water body. In Mexico, the use of herbicides is authorized by the Intersecretarial Commission for the Control and Use of Pesticides and Fertilizers; the herbicides authorized for weed control are glyphosate, ammonium glufosinate, ametrine, 2,4-D, dalapon, dicamba, diuron, paraquat, diquat, simazine and terbutryn [16,95].

Integral Control of Water Hyacinth in Mexico

The studies that reported greater effectiveness in the removal and elimination of this aquatic species proposed the implementation of integrated control methodologies [16,83,87,89], which means the combined implementation of various control elimination methods for water hyacinth. Looking at the development of comprehensive control works in 15 irrigation districts in the country, it was reported that over 10 years, the associated costs were 19.67 million pesos (at 2005 prices), compared to approximately 225 million pesos (at 2005 prices) if only mechanical control had been applied [16]. Ex-

periences with the application integrated control showed that the stage at which the plant is in its weakest state, the sensitivity of the habitat, as well as the climatic conditions of the site, are important factors to consider in identifying the most appropriate control methods.

It is necessary to know that the total and complete eradication of water hyacinth is unlikely and would only be possible in closed water bodies or a small infestation area; when this is not the case, before carrying out any control method, determinant variables such as the area and density of the mat should be considered and, as a precautionary measure, it is necessary to analyze oxygen levels in the water. For instance, if dissolved oxygen is an indicator of poor quality and health for native species (plants and fish), the application of the chemical methods, such as herbicides, could be the most feasible option; also, it could be necessary to identify the source of infestation, which requires economic resources that allow for the continuous monitoring and follow-up (especially in periods of growth) of the control method employed, as well as of the dormant seed bank, which may enable the plant's re-establishment.

The adequate adaptation and implementation of control programs integrating the recovered biomass could promote the conservation of lake ecosystems, and in subsequent years would allow for decreases in the costs of application and the maintenance of water bodies. However, it is worth mentioning that the application of control methods depends largely on the socio-economic context of the Mexican region.

Table 1 provides a synthesis of documented experiences regarding water hyacinth control in Mexico, highlighting the various methodologies implemented over the years. These approaches encompass mechanical, biological, chemical, and integrated control strategies, reflecting diverse management efforts aimed at mitigating the ecological and economic impacts of this invasive species. Taken together, the chronology of events indicates a clear evolution of control programs over time: early reports (1970s) focused mainly on mechanical extraction and crushing as direct operational responses, whereas the mid-1980s and 1990s show diversification toward integrated schemes (e.g., combining operational/infrastructure actions, herbicide validation and application, and mechanical equipment) alongside the first systematic biological-control evaluations and releases using *Neochetina* spp. From the late 1990s through the 2010s, larger-scale and longer-term biological control programs are increasingly reported in irrigation districts (notably in Sinaloa), while some experiences also document limitations associated with discontinuity or local operational dynamics. In the 2000s and 2010s, combined strategies with institutional investment became more common; however, reinfestation episodes underline the need for sustained follow-up. Most recent reports (2017–2023) emphasize integrated management proposals and quantified removal outcomes, suggesting a gradual shift toward multi-method, context-adapted programs rather than isolated interventions.

Table 1. Control experiences with water hyacinth in Mexico.

Event Year[s]—State	Experience	Body of Water	Reference
1974—Michoacán	The first mechanical crusher in Mexico consisted of a boat, with a crushing capacity of 60 tons/day and manual feeding.	Lake Patzcuaro	[72]
1974—Sonora	By using mechanical extraction and crushing methods, it is possible to reduce water hyacinth infestation by 58.3% in two storage dams in Mexico.	La Angostura Dam	[96]
1974—Chiapas		Malpaso Dam	

Table 1. *Cont.*

Event Year[s]—State	Experience	Body of Water	Reference
1985—Hidalgo	Action control by an integrated plan of three lines of action: (1) attention to the mouth of sewage, (2) control of piezometric level to achieve the dry and burn of plants, and (3) installation of a crushing machine of national manufacture with crushing capacity of 44.37 tons/hr.	Requena Dam	[97]
1986—N/A	Manufacture and application of a shredder consisting of a barge equipped with blades, with a penetration capacity of 30 cm below the water mirror. Favorable results in small water bodies.	NS	[97]
1993—Jalisco	Integrated control of water hyacinth, through a combination of the chemical method (application of glyphosate) and mechanical method (application of two crushing machines), achieving 160 and 180 ha of remotion.	Trigomil Dam	[72]
1993—Sonora	Development of a dose validation program for the application of diquat and glyphosate.	Irrigation District 041, Yaqui River	[16]
1993–1994—Sinaloa	Experimental demonstration plots of 2 m^2 with different densities of neoquetines were used in various districts of the country, assessing the efficiency of insects in various ranges of water quality and temperature. The results showed a wide margin of applicability as the insects were able to survive extreme temperature ranges and different water qualities.	Irrigation District 010 Culiacán Humaya	[16]
1994—Jalisco	Mechanical control application in 103 ha in the eastern area of the municipalities of Ocotlán and Jamay.	Lake Chapala	[98]
1995—Sinaloa	Biological control was applied via the open release of 22,137 insects from two species of beetles (*Neochetina bruchi* and *N. eichhorniae*) in 41 specific points, distributed over 18 water bodies. The organisms were deposited inside the bracts of individual plants and distributed among them by the weeds.	Irrigation Districts 010 and 074 Culiacán	[85]
1995–2011—Sinaloa	Insects released in contaminated area of 2700 ha, achieving 300 ha reduction over 16 years, without re-infestation.	Irrigation Districts 010 Culiacán	[16]
1996–1997—Nayarit	A study of insect population fluctuations using the species *Neochhetina* spp. was carried out to learn their behavior and design control strategies, which identified that the plant size influences the host.	Mololoa River	[99]
1998—Jalisco	Experimental demonstration plots of 2 m^2 with different densities of neoquetines were used in various districts of the country, assessing the efficiency of insects in various ranges of water quality and temperature. The results showed a wide margin of applicability as the insects were able to survive extreme temperature ranges and different water qualities.	Irrigation district 024 Ciénega de Chapala	[16]
1998–1999 Sonora		Irrigation District 018 Yaquis Colonies	

Table 1. *Cont.*

Event Year[s]—State	Experience	Body of Water	Reference
1998–2000—Jalisco	Weed control by validating the use of two types of weevils, *Neochetina bruchi* (*Warner*) and *N. eichhorniae* (*Hustache*), as biological agents for water hyacinth control. After two years of application, 100% control was achieved.	Irrigation district 024 Ciénega de Chapala	[88]
1998–2000—Michoacán		Irrigation District 061 Zamora	
1998–2000—Jalisco	Biological control by a program of the release and propagation of neo-kites, without continuity and success due to the dynamics and use of machinery in the irrigation districts.	Irrigation district 024Ciénega de Chapala	[100]
1999—Nayarit	Chemical control of iris by applying the herbicides 2,4-dichlorophenoxyacetic (2,4-D) and glyphosate. 2,4-D was the treatment that presented the best response, showing 100% weed control at 14 days.	Mololoa River	[99]
2002–2003—Puebla	Biological control was evaluated via the capture and release of 23,290 insects of *Neochetina bruchi* and *N. eichhornia*. The results showed that insects are able to adapt to local conditions, even when the months are colder.	Manuel Ávila Camacho Dam	[101]
2003—Puebla	The Ministry of Urban Development, Ecology and Public Works authorized mechanical control (until now) to reduce water hyacinth infestation in the state of Puebla.	Manuel Ávila Camacho Dam	[87]
2004—NS	Application of biological control through the use of control agents; massive release of 9800 neoquetines of the species *Neochetina eichhorniae* and *Neochetina bruchi* and application of sprays of the fungi *Cercospora piaropi* and *Acremonium zonatum*.	NS	[102]
2004—Puebla	Around 15 million pesos were invested to combat the infestation through a combined control strategy, including mechanical removal and the introduction of *Neochetina eichhorniae* and *Neochetina bruchi*. However, two years later, a reinfestation problem was reported in the Ávila Camacho Dam.	Manuel Ávila Camacho Dam	[16]
2007—Morelos	Application of biological control using control agents; massive release of 9800 neoquetines of the species *Neochetina eichhorniae* and *Neochetina bruchi* and application of sprays of the fungi *Cercospora piaropi* and *Acremonium zonatum.* Two months after application, a 29% decrease in fresh weight was observed, and 59% decrease in the total plants per m^2.	Cruz Pintada Reservoir	[74]
2011—Guanajuato	Application of mechanical control through the implementation of a combine harvester with an extraction capacity of 2–4 ha/day, resulting in an extraction of up to 1080 tons.	Yuriria Lagoon	[103]
2012—NS	Application of the mechanical control method for the hydro-agricultural infrastructure [irrigation areas] in the country.	NS	[16]

Table 1. *Cont.*

Event Year[s]—State	Experience	Body of Water	Reference
2013—Guanajuato	Generation of rural employment via water hyacinth eradication programs using manual extraction and burning.	Yuriria Lagoon	[104]
2014—Sinaloa	Total release of 262,000 insects of the species of Neoquetines (*Neochetina bruchi* and *N. eichhorniae*), increasing the density of insects per plant from 1.43 to 5.	Irrigation District 010	[83]
2014—Sinaloa	Over a two-year period, a total of 265,000 neoquetines of the species *Neochetina bruchi* and *N. eichhorniae* were collected and released, controlling up to 90% of the infestation.	Arroyo Prieto Dam	[85]
2014—Michoacán	Removal of 31.78 ha of water hyacinth by mechanical extraction.	Lake Pátzcuaro	[105]
2014—Sinaloa	Biological control plan releasing 262,000 insects of the species *Neochetina bruchi* and *N. eichhorniae*, producing an increase in the density of insects per plant of 1.43 to 5.0 and 1.93 to 3.23.	Mariquita Dam	[83]
2014—Jalisco		Zapotlán Lagoon	
2017—Guanajuato	The Ministry of Environment and Territorial Planning proposed integrated control using a combination of mechanical, chemical and biological control.	Yuriria Lagoon	[106]
2017—NS	Biological control by breeding; monthly mass release of 160,458 insects of the species *Neochetina eichhornia*, *Neochetina bruchi*, and the strain *Acremonium zonatum* over 7 months. The results showed a 30% reduction in infestation.	NS	[107]
2022—Hidalgo	Integrated water hyacinth control combining manual extraction and mechanical method (crushing machine application). A removal of 142.8 ha was achieved, with 76.7% water hyacinth control.	Tecocomulco Lagoon	[108]
2023—Michoacán	The mechanical extraction of water hyacinth was carried out by the Fisheries Commission of the State of Michoacán using the program "Rehabilitation and maintenance of reservoir".	Lake Pátzcuaro	[109]

Note: NS means unspecified.

Alternative Control Methodologies

Other studies on water hyacinth control have not yet been implemented on a large scale; however, at the experimental level, they have shown promising results for potential upscaling to manage proliferation. One of these is photoacoustic spectroscopy (PAS), which aims to monitor the optical absorption spectra of the plant to assess its physiological state, chlorophyll concentration, and stress response under different environmental or treatment conditions. In the studies conducted by Calderón et al. [110,111], *Eichhornia crassipes* was subjected to ultrasonic irradiation at specific frequency and intensity values to induce cavitation in the plant structure, inhibiting its photosynthetic activity. The results showed that 17 kHz and 1.5 mW/cm^2 irradiation produced a decrease in the amplitude of the chlorophyll bands, indicating structural damage to the photosynthetic centers of the plant; this method was more economically viable compared to conventional control techniques. These studies represent the main experimental techniques reported in Mexico

for the physical and optical control of water hyacinth, although research on complementary technologies remains incipient.

3.2. Application of the Biomass Valorization Model in the Utilization of Water Hyacinth in Mexico

The circular bioeconomy emphasizes the sustainable and efficient valorization of biomass through integrated production chains and diversified products [54]. Biomass valorization is central to this approach, as chemical, biochemical, thermochemical, and biological processes enable the conversion of biological resources into high-value products before final disposal. This perspective has led to hierarchical models that prioritize high-value, high-complexity uses over energy recovery or waste treatment. Among these models, the biomass valorization pyramid highlights that products with greater economic value and technological complexity are placed at the top, while lower-value and less complex outputs occupy the base [54,59,112,113].

According to Davis et al. [59], the recovery pyramid classifies biomass-derived products into four value-based levels. At the top, the "Health and Lifestyle" level includes pharmaceutical and fine chemical products, considered high value because they aim to improve population health and quality of life. The next level, "Food", encompasses food and feed, both with significant bioeconomic potential. In the intermediate level, "Chemicals and Materials," are high-performance materials (biomaterials and bioplastics), commodity chemicals, fertilizers, and bulk chemicals, which are generally low-cost and still lack sufficient governmental support for large-scale deployment. At the base, the "Energy" level includes biofuels, heat, and electricity generation, as these products have limited potential for value retention or reuse [54].

Within the same hierarchical logic, and from an educational perspective, Márquez Luzardoa & Venselaar [112] introduced the concept of biocascading, in which biomass is first directed toward industrial applications that yield high-value products before being degraded for energy recovery. These approaches highlight the need for reuse and recycling strategies at each level of the value pyramid to ensure that every biomass fraction is directed to the most suitable transformation pathway. However, Stegmann et al. [54] note that significant challenges remain for implementing the recycling pyramid, mainly due to insufficient economic infrastructure and limitations in integrating biodegradable raw materials into production cycles. Therefore, strengthening public policies that promote biomass reuse in strategic sectors remains essential.

Based on the hierarchical model of the biomass valorization pyramid, an analysis was conducted of the documented uses and applications of, and bioproducts derived from, water hyacinth. A total of 109 studies were reviewed, including experimental research, reviews, technical reports, and theses published between 1972 and 2023. Each identified use was classified according to the four levels of the valorization pyramid: (1) Health and Lifestyle, (2) Food, (3) Chemicals and Materials, and (4) Energy. It is important to highlight that 25% of the publications focused solely on determining the chemical composition, physical properties, elemental profile, and characterization techniques of water hyacinth, without explicitly linking these findings to a specific use or application. Consequently, these studies were not included within the hierarchical scheme, although their results are reported and discussed separately due to their relevance to understanding the potential of water hyacinth within biomass valorization processes.

The results are presented below (Figure 5), classified according to the recovery level and organizing the uses and bioproducts derived from water hyacinth according to the added value they provide within the bioeconomy model. This structure makes it possible to identify areas with greater technological development, as well as those with growth potential and opportunity gaps.

Figure 5 shows the distribution of uses of *Eichhornia crassipes* as raw material—either transformed into bioproducts or used directly—across the four levels of the biomass recovery pyramid. A total of 70.7% of the studies fall within the "Chemicals and Materials" level, where applications such as compost and vermicompost production, biocomposites, absorbent fibers, and soil improvement are predominant. The second most represented category is "Energy" (12.2%), including bioethanol and biogas production. Meanwhile, 9.8% of the publications correspond to the "Health and Lifestyle" level, such as the pharmacological potential of extracts, nanoparticles, and microorganisms associated with water hyacinth. Finally, only 7.3% relate to the "Food" level, mainly involving its use as fodder or feed supplement. This distribution indicates that scientific and technological development is concentrated in the intermediate levels of the pyramid, while high value-added levels remain comparatively less explored.

In this context, incorporating biomass into biorefineries stands out as one of the most comprehensive utilization strategies. Biorefineries are key to productive integration because they enable the generation of diverse bioproducts from biomass. Santibañez-Aguilar et al. [114] developed a superstructure and a multi-objective optimization model for sustainably managing water hyacinth through a distributed biorefinery system aimed at producing biofuels and specialty chemicals, maximizing biomass removal while minimizing costs. Their case study in one of Mexico's main hydrological regions demonstrated that distributed biorefineries can support both weed control and bioeconomic development. More recently, Martínez Ruiz & Méndez González [115] reported on LirMex II, a pilot-scale biorefinery in Xochimilco (Mexico City) designed to convert water hyacinth into compost, vermicompost, biogas and absorbent materials using a zero-waste approach. The facility has processed over 17 tons of biomass and has shown economic viability and environmental benefits, positioning it as a scalable model.

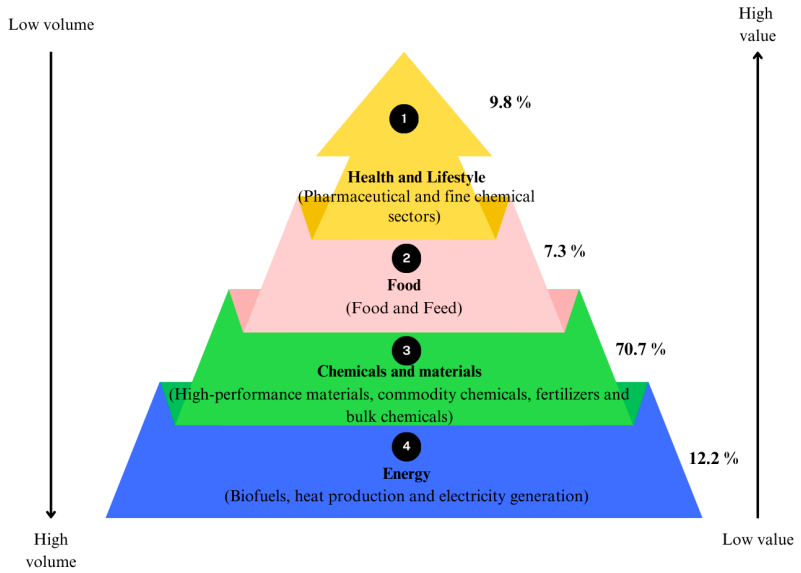

Figure 5. Percentage distribution of uses of *Eichhornia crassipes* according to biomass recovery levels.

3.2.1. Geographical Distribution of Water Hyacinth Extraction and Its Exploitation in Mexico

Among the studies analyzed, it was identified that 72.3% of the investigations explicitly report the Mexican states and the water body from which the water hyacinth was extracted and recovered for reuse, whereas 27.7% of the studies do not provide such information. With respect to geographic distribution, the states that reported on the extraction of *Eichhornia crassipes* include Colima, Durango, State of Mexico, Guanajuato, Guerrero,

Hidalgo, Jalisco, Michoacán, Oaxaca, Puebla, San Luis Potosí, Sinaloa, Sonora, Tabasco, Tamaulipas and Veracruz.

The analysis by Federal Entity shows that the exploitation of water hyacinth in Mexico presents a differentiated distribution according to the levels of biomass recovery. As shown in Figure 6, in Colima, 100% of the studies focused on applications at level 2, "Food", mainly linked to the use of water hyacinth as a forage input. In Durango, the approaches were divided equally, with 50% of the work oriented at level 1, "Health and Lifestyle", and the remaining 50% focused on "Food". In the State of Mexico, 71.4% of the research focused on the development of chemicals and materials (Level 3) while 28.6% addressed human health applications. In Guanajuato, 75% of the studies concerned the level "Chemical and Materials", and 25% were directed towards energy production (Level 4). In contrast, in the states of Guerrero, Hidalgo, Jalisco, Oaxaca, Sonora, Tabasco and Tamaulipas, 100% of the research was grouped at the "Chemicals and Materials" level, reflecting a focus on industrial applications and physical–chemical transformation. In Michoacan, 72.7% of the studies were located at the "Materials" level, while 18.2% explored alternative uses for energy recovery. Puebla showed a similar behavior, with 60% of studies focused on materials and 20% on energy. Finally, in Veracruz, the distribution was more diversified: 62.5% for materials, 25% for energy and 12.5% for food.

Thus, according to the previous information, the "Chemicals and Materials" level is predominant in most entities, consolidating itself as the main technological route of water hyacinth recovery in Mexico, followed by energy applications, animal feed and, to a lesser extent, human health.

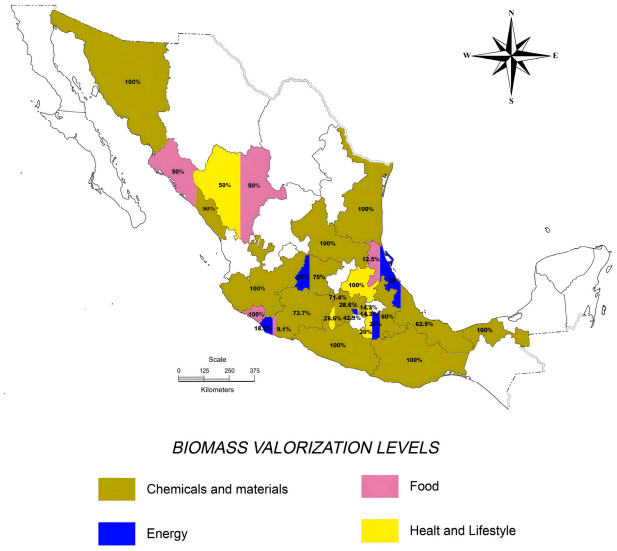

Figure 6. Percentage distribution in Mexico of the valorization of water lilies based on the biomass valorization pyramid.

3.2.2. Level 1: Health and Lifestyle (Pharmaceuticals and Fine Chemicals)

This level, located at the top of the biomass recovery pyramid, includes the water hyacinth-derived products with the highest added value, focusing on the pharmaceutical, medical and cosmetic sectors. These applications require specialized technologies such as advanced extraction and purification, chemical synthesis, and molecular characterization. The following sections present and discuss the applications classified within this level.

Water Hyacinth as a Source of Bioactive Extracts

Natural products, whether isolated compounds or standardized plant extracts, are valuable sources for drug discovery due to their exceptional chemical diversity [116]. Research on natural molecules has centered on plants because they are accessible and can be selected by their ethnomedicinal relevance. One of the reported approaches to water hyacinth is using it as an alternative source of medicinal compounds, since leaf extracts contain tannins, alkaloids and flavonoids [117], which are known for their antibacterial, antiviral and antifungal activities. López-Medina et al. [36] analyzed the proximate and phytochemical composition of several extracts and confirmed their bacteriostatic potential. Their phytochemical analysis showed that bulb, leaf and leaf–bulb tissues contain flavonoids, tannins, saponins and phenols, with aqueous extracts presenting the highest concentration of bioactive compounds. Regarding the microbiological use of the plant, several endophytic fungi—microorganisms that colonize internal tissues without causing damage and provide protective effects—have been isolated [118]. Trigos et al. [119] isolated the phytopathogenic fungus *Cercospora piaropi* from water hyacinth leaves and obtained the compound epi-cercosporin. Spectroscopic analyses showed that epi-cercosporin exhibited in vitro antiproliferative activity against human solid tumor cell lines WiDr (colon), SW1573 (lung), HeLa (cervix) and HBL-100Q (breast), although it was less active against the more resistant T-47D (breast) line. Extracting target components is the first step in microbial analysis, followed by separation and characterization [120,121]. In the study carried out by Fileto-Pérez et al. [122], samples of derivatized extracts from the leaves, stems and roots of *Eichhornia crassipes* were analyzed using the soxhlet technique for 6 h; hexane, cyclohexane, acetone and methanol were used as solvents, before their subsequent evaporation at a temperature of 40 °C. The samples were analyzed by gas chromatography and mass spectrometry (GC/MS). The results indicated the presence of 20 organic acids (levulinic, oxalic, caprylic, malonic, nonaic, succinic, myristic, lauric, linolenic, palmitic, oleic, vaccenic, linoleic, arachidonic, F-talic acid and tetradecanoic, pentadecanoic, 10,12-octadecadiene, octadecanoic and tetracosanoic acid), 3 steroids (cholestane, spirostatane and β-stigmasterol) and 1 terpenoid (squalene), which are of great interest due to their potential uses in the pharmaceutical industry.

Obtaining Fructans

Fructooligosaccharides (FOS), also called oligofructans or fructans, are short-chain carbohydrates composed of fructose and glucose residues. The term FOS is the standard biochemical designation for these naturally occurring prebiotics, which encompass a wide diversity of polysaccharides [123]. FOS consist of repetitive disaccharide units such as levanobiose, inulobiose and sucrose, and the binding of fructosyl groups to sucrose forms ketoses, the natural fructans [124]. These compounds have multiple important implications for human health, including immune function enhancement, improved nutrient bioavailability during fermentation, dietary fiber functionality, and a recognized prebiotic effect due to their biological and physicochemical properties [123,125]. They are also in high demand in the food industry and can be used as non-carcinogenic, low-calorie substitutes in various foods because of their nutritional characteristics [126].

It has been reported that up to 36,000 species of plants contain various types of oligofructans in their structure [127]. In the study carried out by Rodríguez et al. [128], the optimal extraction of fructans from the plant *E. crassipes* was presented, highlighting that the plant was used in the phytoremediation of effluents from aquaculture farms. They quantified the fructans and their specific measurement in plant extracts. Also, the authors carried out an optimization process for fructan extraction using a Box–Behnken 3 3 factorial design, with a total of 15 experimental runs; the variables of interest were

temperature, extraction time and the liquid–solid ratio. The optimal values obtained for a theoretical extraction were 257.61 mg/L at 71.81 °C, with an extraction time of 75.72 min and a liquid–solid ratio of 5.07 mL/g.

Nanoparticles Synthesis

Nanotechnology has become one of the most influential technologies across scientific disciplines [129], relying on the synthesis and modulation of nanoparticles (NPs) through the transformation of metal properties. Nanoparticles have diversified applications in environmental, biomedical and physicochemical fields, as well as in the pharmaceutical, industrial and agricultural sectors [130]. Their synthesis using plants, microorganisms, enzymes or algae—known as phytonanotechnology—is considered a green, simple, rapid, scalable and biocompatible approach. This technique offers advantages such as eliminating toxic reducing agents, reducing energy demand, enhancing biocompatibility and improving environmental sustainability [131,132], supported by the high availability and non-toxic nature of biological resources [130]. It has been reported that the bioreduction process, which is useful in nanoparticle synthesis, when used in water hyacinth under standard pressure and temperature conditions (1 atm and 25 °C), promotes the formation of metal particles, in addition to a rapid synthesis rate [133]. Various parts of the *Eichhornia crassipes* plant, such as the leaves and stems, have been used for the synthesis of metal nanoparticles [134,135]. Munive-Olarte et al. [133] synthesized silver and gold nanoparticles using $AgNO_3$ and $HAuCl_4$*$3H_2O$, respectively, as precursors, and employed leaf biomass extracts of *Eichhornia crassipes* as natural reducing and stabilizing agents. The authors evaluated the effect of pH on the process optimization, identifying that this parameter influences the particle size; the formation of small nanoparticles was favored by an acidic pH. For AgNPs, it was determined that an acidic pH (pH = 5) improved their formation, achieving sizes ranging from 1 to 10 nm with a character-centered hexagonal cubic structure. On the other hand, for AuNPs, a neutral pH (pH = 7) led to the smallest diameter and less dispersed nanoparticles with an orthorhombic structure. In other study, Silva et al. [135] synthesized Ag nanoparticles with a polyhedral structure from different parts of *Eichhornia crassipes* (roots, leaves and stems) using $AgNO_3$ as a precursor via the bioreduction method. According to the results, the amounts of hydrolyzable tannins contained in each plant structure influenced the shape, size, structure and composition of the synthesized nanoparticles; additionally, at 5 mg/L, the Ag nanoparticles synthesized with leaves (as they have the highest amount of tannins with respect to the stems and roots) led to 100% inhibition rates for bacterium *Escherichia coli* ATCC 25992, in contrast to a commercial solution that needed 10 mg/L of Ag. On the other hand, Velázquez-Hernández et al. [134] used the phytosynthesis process in the water hyacinth extract to obtain TiO_2 nanoparticles (TiO_2 NPs); their photocatalytic activity and their microbicidal effectiveness against the *S. aureus* and *E. coli* strains was demonstrated. Their results indicated that at an acidic pH, TiO_2 NPs had better photocatalytic efficiencies.

Bioorganism Producer

Studies have examined the isolation of free-living amoebas (FLA), classified by habitat into water, soil and air [136]. These organisms are medically relevant due to their ubiquity, the high virulence of their parasitic forms, and their ability to cause fulminant diseases [137]. Ramirez et al. [138] isolated free-living amoebas from water hyacinth root because this provides a suitable habitat for organism's growth inside its structure. The isolation process was carried out at two temperatures, 30 °C and 37 °C, with 5 gr root samples planted in non-nutritive agar with enterobacter aerogenes (NNE). This isolation obtained 16 genera: *Acanthamoeba*, *Cochliopodium*, *Dactylamoeba*, *Echinamoeba*, *Hartmannella*, *Leptomyxa*, *Mayorella*,

Paradermamoeba, *Platyamoeba*, *Polychaos*, *Saccamoeba*, *Thecamoeba Vahlkampfia*, *Vexillifera*, *Naegleria* and *Vannella*. According to the results, the highest incidence of trophic forms was observed in roots at an average temperature of 29 °C, and in leaves and roots at 35 °C, with Acanthamoeba showing the highest growth in water hyacinth roots at 28 °C. These applications demonstrate a growing interest in water hyacinth as a source of high-value bioactive compounds within the bioeconomy; however, research in this area remains limited and mostly experimental, indicating substantial potential for further development.

3.2.3. Level 2: Food (Food and Feed)

This recovery level includes uses where water hyacinth is incorporated directly or indirectly into livestock and fish diets, highlighting its economic viability and availability. Compared with other levels, these applications generally require minimal processing or even direct biomass use.

Water Hyacinth as Animal Fodder

Rising food production costs, limited animal protein sources, and rapid population growth have intensified the global need for food security, prompting the search for unconventional food sources and affordable, accessible supplements [139]. Water hyacinth research has promoted it as an excellent animal food due to its nutritional value, and water and mineral content [140]. Its protein concentrate can be combined with other foods to produce excellent-quality protein sources for animal feed formulation [141]. Several researchers have studied water hyacinth as a possible substitute for alfalfa in the diet of various animals. Pámanes et al. [141] evaluated its inclusion in the diet of cattle and tested different levels of substitution [0%, 24%, 50%, 75% and 100%], determining that the inclusion of water hyacinth in the bovine diet produces a reduction in emissions of ruminal methane and CO_2. Likewise, Tejada de Hernández [142] progressively replaced alfalfa with water hyacinth, introducing full water hyacinth flour, bulb flour and water hyacinth leaves in the diet of growing chickens, in order to determine the nutritional value of the plant; these experimental studies indicated that it does not contain toxic factors for the growing chicken. However, its low metabolizable energy and its high amount of crude fiber could affect its inclusion in diets. Rodríguez & Bravo [143] quantified the apparent digestibility coefficients in sheep by introducing a diet containing 80% water hyacinth flour. The apparent digestibility coefficients of water hyacinth were as follows: raw protein 63%, crude fiber 40%, dry matter 72%, ash 71%, 58% free extract and 68% nitrogen. The authors reported no adverse effects or behavioral alterations in the animals fed with water hyacinth flour, indicating an acceptable level of tolerance to the inclusion of this biomass in the diet. Within this same field, the water hyacinth has been used as a complementary ingredient in fish feed. Reyes [144] formulated a tilapia feed from a fermented mixture of water hyacinth and cane molasses using *Lactobacillus acidophilus*; the fermentation product was blended with commercial basal feed and supplemented with different proportions of corn flour [30%, 60% and 10%] according to each treatment formulation. The study reported that the inclusion of fermented water hyacinth reduced feed production costs by approximately 25–30%, without significant differences in growth rate, feed conversion ratio, or survival compared to the control diet, demonstrating its potential as a sustainable partial substitute in small-scale aquaculture systems. A similar study was presented by Díaz Galaviz [145], which evaluated water hyacinth's use as a substrate in tilapia food. The study concluded that water hyacinth insertion was favorable and economically viable; however, monitoring was required. Vázquez Hernández & Guzmán González [146] evaluated the efficiency and compared the nutritional performance of foods from various aquatic weeds, including water hyacinth, with a commercial balanced feed for feeding herbivorous carp crops. Their

results showed that although commercial food generated the highest growth rates, water hyacinth-based food presents an acceptable performance to be considered as a complementary food; however access to commercial inputs is still limited. These studies support the potential of the plant as a low-cost alternative in fish diets.

Safety and Risk Constraints

Although Level 2 applications (Food and Feed) and health-related products represent higher-value routes, their feasibility is strongly constrained by safety requirements. *Eichhornia crassipes* is widely documented as a phytoremediator and can therefore bioaccumulate contaminants present in the water body [including heavy metals and metalloids such as arsenic], creating a direct risk of transfer into the food chain if biomass from impacted sites is used as a food or feed input [147–152]. In addition, recognized feed safety guidance notes that materials intended for feed/food may involve undesirable and hazardous substances such as heavy metals, chemical contaminants and mycotoxins, as well as microbiological contamination risks; therefore, higher-value applications require source control, adequate pre-processing, and sampling–analytical schemes to verify compliance with applicable standards [153]. Accordingly, in this review, food/feed/health valorization routes should be interpreted as conditional pathways: they are only appropriate when the biomass source is verified (e.g., non-impacted waters or controlled cultivation) and when processing and monitoring measures demonstrate compliance with contaminant limits and safety requirements under recognized frameworks (e.g., Codex principles and maximum levels for contaminants in food and feed, and regulatory criteria for undesirable substances in feed) [154]. For Mexico, these routes should also be aligned with the national regulatory framework applicable to products for animal use or consumption [155].

3.2.4. Level 3: Chemicals and Materials (High-Performance Materials, Commodity Chemicals, Fertilizers and Bulk Chemicals)

This recovery level includes water hyacinth uses that require functional biomass conversion to obtain bioproducts for environmental, industrial and agricultural applications. Although these products are not considered high-value within the circular economy compared to pharmaceutical derivatives, they offer significant potential regarding their applicability and scalability. The review found that 62.1% of reported uses in Mexico fall within this level, including compost and organic fertilizer production, the adsorption of heavy metals and dyes, biochar and biopolymer synthesis, and the development of absorbent and construction materials synthesized from the plant's fibers.

Water and Soil Treatment

1. Biofilters Synthesis

Growing social pressures have increased global water demand [156], which is increasingly difficult to meet due to environmental and anthropogenic pollution [157]. As a result, protecting water resources has become a major concern. Traditional physical, biological and chemical treatments—such as reverse osmosis, ion exchange, electrodialysis, chemical precipitation, flocculation and activated-carbon adsorption—have been used to remove contaminants [158], though their effectiveness depends on contaminant type and concentration. These methods also present drawbacks, including waste generation, environmental impacts, low profitability, on-site limitations, difficulties in their integration with other methods, and inconsistent contaminant removal [159,160]. Given these challenges, research has shifted toward techniques that offer effective pollutant removal, easy application, scalability and greater environmental compatibility. In this context, biofilters, or bioretention systems, use plants to promote evapotranspiration and infiltration [157,161] and have emerged as

a highly viable option for improving polluted water effluents. The use of biofilters has become a highly viable option for improving the quality of polluted water effluents. The use of the invasive species *Eichhornia crassipes* as a renewable feedstock in the synthesis of biofilters was reported by Camacho Martínez [162]. In his study, the physicochemical and structural properties of the plant were analyzed, and functionalized fibers derived from its lignocellulosic biomass were developed for oil–water separation applications. The resulting material exhibited high adsorption capacity and chemical stability, achieving separation efficiencies above 80%.

2. Organic Biosorbents

The remarkable properties and potential applications of biomaterials have positioned them as innovative environmental solutions [163]. Biosorbents are biomaterials capable of absorbing and retaining aqueous fluids [164]. They may originate from microorganisms, bacteria, fungi, marine algae or plants, with water hyacinth standing out as an excellent raw material for sorbent production [165,166]. Vázquez et al. [166] developed a biodegradable polysaccharide absorbent from water hyacinth and carboxymethylcellulose, with the ability to form gel liquids at room temperature, varying the composition of each material. In the first stage, the maximum absorption capacity of the water hyacinth stem in the maturity stage was evaluated by means of a triplicate test by adapting the ASTM F-726 standard [167] and the Canadian protocol "Oil Spill Sorbents": Testing Protocol and Certification Listing Program". The maximum absorption capacity reported by the stems was 16.5 ± 1.1 g/g of absorbent, while the sorbent produced achieved an absorption of 26 g, with the maximum absorption of material at 35.7 ± 8.6 with 1.5 g of water hyacinth and 0.4 g of carboxymethylcellulose. Then, in the study carried out by Islas et al. [165], water hyacinth was used for the production of bioabsorbents through a fragmentation process of the rhizosphere. The resulting material showed high efficiency in removing heavy metals such as zinc, lead, copper and cadmium from contaminated water, with removal rates exceeding 70% depending on the metal type and pH conditions. Later, the synthesis of adsorbent powders from water hyacinth for the removal of cobalt (III) was addressed by Acosta-Rodríguez et al. [168], wherein cobalt removal was evaluated in a pH range 4.0–8.0 for 48 h, from 20 to 50 °C, with different initial concentrations of the pollutant in the range 100–500 mg/L. The highest bioadsorption, corresponding to 100 mg/L, was obtained at pH = 5, 25 °C and an operating time of 28 h, showing a removal capacity of 73.1%. Finally, Juárez [169] evaluated the efficiency of magna gasoline removal using an oleophilic sorbent powder with water hyacinth as a carrier, in combination with three species of fungi, *Trichoderma harzianum*, *Aspergillus niger* and *Fusarium solani*, with the latter being the most efficient strain, removing up to 72% of the total hydrocarbons in the oil. Also, it was observed that powdered water hyacinth does not inhibit fungus growth, which increases its viability as a support material in bioremediation processes.

3. Seawater Desalinator

Water scarcity has driven the search for technologies that enable the use of seawater as a potable resource, though current methods require significant investment. The evapotranspiration process performed by water hyacinth could reduce the energy demand of desalination, making the production of drinking water more economical. Arámbulo-Miranda & Ruelas-Ramírez [170] conducted an exploratory study in which *Eichhornia crassipes* was favorably adapted to saline environments using hydrogen peroxide (H_2O_2) as an inhibitor of the slow vacuolar channel. Under these conditions, the plant exhibited high salt tolerance (100%) and was able to perform evapotranspiration as a natural mechanism for salt elimination, evidenced by salt crystallization on the leaf surface. Subsequently, Arámbulo-Miranda & Ruelas-Ramírez [171] evaluated the physiological and morphological

effects associated with H_2O_2-induced saline stress tolerance. Their results confirmed that a concentration of 0.03% H_2O_2 promoted tolerance levels comparable to those found in seawater salinity, suggesting that water hyacinth could serve as a biological model for sustainable and low-cost seawater desalination processes.

Applications in the Agricultural and Fertilizer Sector

1. Composting

As an organic and nutrient-rich material, water hyacinth contributes to soil organic matter and enhances its biological and physicochemical properties [172]. Considering the problems associated with its infestation—eutrophication, loss of endemic species and blockage of waterways—composting emerges as a suitable strategy for biomass management. Composting is an oxidative, biologically driven and eco-economically viable process [173] involving the aerobic and anaerobic transformation of organic matter by microorganisms such as bacteria and fungi. These organisms decompose substrates into carbon dioxide, methane, ammonia and water vapor, releasing heat and producing humus. The efficiency of composting and the nutrient quality obtained depend on factors such as microbial metabolism, temperature, moisture, pH, oxygen availability and the C/N ratio [174,175]. Several studies have documented the use of water hyacinth as a primary organic waste when combined with other substrates in composting processes. Also, it has been reported that the fertilizer from water hyacinth is one of the four most used organic fertilizers today, since it makes it possible to take advantage of crops and animal residues, transforming them into organic matter and increasing the yield, the protein and the nutrient content, which makes it a perfect substitute for conventional fertilizers [176,177]. One of the main purposes in the elaboration of compost from water hyacinth has been its use as propagating medium. In the study carried out by Sañudo-Torres et al. [178], composts were made from the plant in combination with other wastes, such as dead soil with leaf litter, bovine manure, wheat bran and bat guano, with the aim of using compost in combination with soil as a substrate in propagation and pre-germination treatments of the Palo Fierro seed (Olneya tesota A.Gray). The composting process lasted 90 days, during which the beds were kept at a temperature below 50 °C, manually turning the biomass every 15 days using the shoveling technique. The resulting compost improved soil moisture retention and aeration, promoting seed germination rates above 80% and vigorous seedling growth compared to control soil. The authors concluded that water hyacinth-based compost represents a sustainable and low-cost alternative for forest nursery production in arid regions.

Another study focused on optimization of the operating parameters of composting using water hyacinth as raw material, in order to obtain fertilizers with the highest amount of nutrients and low presence of pathogenic microorganisms [179]. Barleló Quintal et al. [180] studied the aerobic dynamic composting process of water hyacinth and sheep excreta, using different mixing ratios of 100L/0E, 75L/25E/, 50L/50E, 25L/75E and 0L/100E (where L refers to water hyacinth and M to manure), monitoring humidity, temperature and pH every third day. Once the compost was obtained, germination tests were carried out on coriander and radish seeds. Among the treatments, the compost with a 75L/25M ratio showed the best characteristics in terms of seed germination and compost quality. Then, in 2015, Tello-Andrade et al. [181], reported the composting of water hyacinth with sludge at different concentrations, using reduced-size water hyacinth to favor biodegradation and microbial attack in the fermentation. The fermentation stage was carried out in a discontinuous system to increase the production of volatile fatty acids (0.34 g/kg fresh-water hyacinth) and soluble organic carbon. The fermented water hyacinth improved the quality of the compost when used in proportions of 25% and 50%.

On the other hand, the elaboration of compost using sewage sludge and water hyacinth has been reported by Moleón-Jiménez et al. [182]. In their research, composting trials of these raw materials were carried out, studying the addition of amendment substrates (pineapple residues, banana peel and sawdust) to accelerate the composting process, as water hyacinth shows resistance to biodegradability due to its lignin content. The composting system consisted of a static system with aeration. Four piles with different compost compositions of sewage sludge and water hyacinth (100% sewage sludge; 75% sewage sludge and 25% water hyacinth; 50% residual sludge and 50% water hyacinth; 25% residual sludge and 75% water hyacinth) were prepared. In accordance with the results, the pile volume, pile porosity, particle size, and ambient temperature were of great importance to maintain the proper aerobic conditions for the composting process. In the same way, Barceló-Quintal et al. [183] compared vermicomposting (composting by worms) with the traditional composting of water hyacinth, municipal waste and sheep excreta; the parameters used to evaluate the quality of the compost were organic matter content, organic carbon, nitrogen, C/N ratio and phosphorus. The best-performing compost consisted of a composition of 50% water hyacinth, 45% municipal waste and 5% sheep excreta, as it achieved a C/N ratio of 15.17, organic matter content of 37.92% and phosphorus concentration of 0.41%, indicating a mature and nutrient-rich compost suitable for agricultural use.

Miranda-González [184] compared the process of composting water hyacinth and manure from various sources (horse manure, cows and chickens) and its application in different proportions as a propagation medium for *Sagittaria macrophylla*, an endangered plant native to Mexico. Their results showed that the treatment with 100% water hyacinth was most effective in promoting greater vegetative development, specifically in terms of the number of leaves, height and the generation of sprouts. Finally, in 2021, Aguilar-Serrano [185] investigated whether water hyacinth was a suitable substrate to accelerate the aerobic composting process of avocado and biosolid waste, using three batches with variable plant proportions (23.48%, 23.72% and 25.26%); the parameters for assessment of the compost quality were organic matter content, carbon, total nitrogen, C/N and pH. According to their results, the addition of dried water hyacinth and biosolids during the composting of avocado residues significantly accelerated the stabilization process, allowing for the safe use of the compost with shorter retention times. The incorporation of *Eichhornia crassipes* reduced the retention period from 90 to 60 days and improved the C/N ratio to approximately 13:1. The composting process reached thermophilic temperature between 55 and 60 °C and a final pH close to neutrality (7.2–7.4), meeting the stability and maturity criteria established by the NOM-004-SEMARNAT-2002 for agricultural application.

Table 2 shows the various substrates used in the production of compost, as well as some quality parameters of the compost obtained.

2. Vermicompost

Since the "Green Revolution" of the 1960s, the prolonged use of chemical fertilizers has greatly increased food production, meeting nearly 50% of the global nutritional needs [186]. However, their intensive and improper use has generated environmental harm, including soil degradation, rhizosphere disturbance, acidification and health risks [187,188]. This has reinforced the need for more sustainable agriculture through environmentally friendly alternatives such as biofertilizers, green manures and vermicompost.

Vermicomposting is a non-thermophilic process in which organic waste is converted into fertilizer through the combined activity of thermophilic microorganisms and earthworms [189]. Vermicompost has been shown to improve soil properties—structure, aeration, porosity, pH, conductivity and organic matter content—enhancing crop growth and yield [190,191].

Table 2. Quality of compost obtained from water hyacinth.

Compost Composition					Composting Method	Humidity	Composting Operating Time	Compost Quality Parameters [% Dry Base]					Reference
								MO	CC	NT	C/N	pH	
Avocado peel and seed	Avocado scar	Avocado seed	Solid Guy	Water Flow									
442.70%	-	-	333.80%	223.48%	AStatic sawing	660%	885 days	440.31	223.37	11.94	112.04	77.84	[185]
-	331.77%	-	444.49%	223.72%				339.78	223.07	11.66	113.89	66.32	
-	-	339.42%	335.30%	225.26%				337.66	221.84	11.72	112.69	77.43	
Sewage sludge				Water Flow									
100%				--	Dynamic sawing	331.56%	1198 days	221.67	NS	442.51	66.14	88.54	[181]
75%				225%		332.42%		445.99	NS	337.01	77.23	77.79	
50%				550%		443.44%		449.4	NS	331.93	99.01	55.54	
25%				775%		558.21%		555.87	NS	221.67	115.04	44.53	

Note: NS means unspecified; MO means organic matter; CC means organic carbon; NT means total nitrogen; and C/N means carbon to nitrogen ratio.

There has been growing interest in vermicomposting, particularly using *Eichhornia crassipes*, in Mexico, with assessments focusing on the environmental, economic and social benefits of its production and applications, given its demonstrated ability to enhance the growth of fungal crops and various vegetables [192,193] through the stabilization of, and reduction in, pathogens in wastewater sludge [194,195]. As previously mentioned, vermicopost from water hyacinth has been evaluated to reveal how it affects the growth of various seedlings. Rios Lira [196] analyzed the physical and chemical properties of vermicopost obtained from a mixture of 70 kg of water hyacinth and 50 kg of cow manure; the process lasted three months, with the raw material being subjected to a pretreatment of solar drying for a month at roughly 30 °C, before adding the worms. The compost obtained was applied as substrate to evaluate the growth of seedlings *Ocimum basilicum*, *Eruca sativa* and *Carica papaya*. The results showed that the vermicompost favored the germination and initial development of *Ocimum basilicum* and *Eruca sativa*, respectively, while for *Carica papaya*, a slow growth but greater root development was observed. Álvarez Bernal et al. [192] analyzed the vermicomposting process with three treatments: T1, with 100% water hyacinth, T2, with 100% cow manure, and T3, with 50% water hyacinth + 50% cow manure. The process lasted 110 days and used *Eisenia feida Savigny*. The results showed that the use of water hyacinth in the vermicompost process led to a stable, mature and nutrient-rich material, resulting in appropriate compost to be used as a substrate and replace commercial fertilizers. The study of Ramírez Leyva et al. [197] determined the viability of water hyacinth as a potential raw material for vermicompost production and its effect on plant development in vegetable seedlings through an experimental design with five treatments (treatment 1: 50% water hyacinth without roots and 50% bovine manure; treatment 2: 50% water hyacinth without roots and 50% vegetable waste; treatment 3: 25% water hyacinth, 25% recycled paper, and 50% vegetable waste; treatment 4: 50% water hyacinth and 50% equine manure; treatment 5: 100% water hyacinth). Plant height was evaluated as the response variable at 15 days post-germination. The most favorable results were observed with treatments 2, 3, and 5, with heights of 13.5 cm, 9.5 cm, and 12 cm, respectively. The results of various studies have indicated that water hyacinth is a potential raw material in vermicompost production due to its nutrient content, and this procedure has also helped in the proper management of its proliferation.

Table 3 shows some parameters used to assess the quality of various vermicomposts produced in Mexico.

Table 3. Quality parameters of various vermicopostas obtained in Mexico.

Composition of Vermicompost			Species of Earthworm Used	Vermicomposting Operating Time	Compost Quality Parameters							Reference
					MO	C	NT	C/N	pH	Humidity	Conductivity	
water hyacinth	Cow manure	Red worm	*Eissenia foetida*	90 days	50.60%	29.30%	2.29%	19.8	8.96	49.40%	5.8 dS m^{-1}	[196]
56.90%	40.65%	2.44%										
Water hyacinth aerial part + corn stover			*Eissenia foetida*	90 days	59.50%	NS	1.73%		8.8	40–70%	6.4 dS m^{-1}	[193]
Water hyacinth with root + barley straw					84.50%	NS	1.32%	34.39	5.2		2.8 dS m^{-1}	
Water hyacinth with root + wheat straw					97%	NS	1.17%	NS	2.4		1.6 dS m^{-1}	
100% water hyacinth			*Eissenia foetida*	110 days	NS	255 g/kg	NS	NS	8	80%	3.34 dS m^{-1}	[192]
Water hyacinth 50% + cow dung 50%					NS	224	NS	NS	9.4		4.01 dS m^{-1}	
Water hyacinth 30% + sewage sludge 70%			*Eissenia foetida*	30 days	60.00%	NS	2.50%	NS	7.2	70%	4 dS m^{-1}	[194]

Note: NS means unspecified, MO means organic matter, C means organic carbon, NT means total nitrogen and C/N means carbon to nitrogen ratio.

3. Uses of water hyacinth as a substrate

One of the various uses for water hyacinth is as a substrate and source of carbon for the production of fungi strains [198]. Water hyacinth was used as a growth medium for five strains of fungi, *Trichoderma harzianum*, *Trichoderma atroviride*, *Penicillium griseofulvum*, *Penicillium commune* and *Aspergillus versicolor*, with the aim of producing hydrolytic enzymes (cellulase and hemicellulases). According to their results, Trichoderma harzianum was the fungus with the highest production of xylase, cellulase and β-d-xylopiranosidase, yielding 149.3 ± 14.3 IU/gdm (where IU/gdm means International Units of enzyme activity per gram of dry matter) at 108 h, 16.4± 0.6 IU/gdm at 84 h and 127.7 ± 14.8 IU/gdm at 48 h. Aspergillus versicolor was the largest producer of the arabinofuranosidase enzyme, with 129.8 ± 13.3 IU/gdm after 108 h. Then, in the study carried out by Cruz-Montes et al. [199], the production of the CP-50 strain of Pleurotus ostreatus on water hyacinth was evaluated, along with its combinations with other substrates, such as wheat straw, corn stubble and barley straw. The best yields were obtained with barley straw and corn stubble (1:1), reaching a yield, colonization time and biological efficiency of 1367.8 g, 15 days and 120%, respectively. Martínez Mayorga [200] studied the production of *P. ostreatoroseus Sing*. on various substrates, including water hyacinth stubble. The substrates received a fermentation pretreatment, then underwent a process to stop the growth of microorganisms before the sowing of mycelium; the inoculated material was placed inside an incubation room for proper mycelium colonization and growth. The total mushroom production was 2312.31 g with a biological efficiency of 115.60%. In 2016, Hermoso-López Araiza et al. [201] cultivated the fungus *P. ostreatus* on four different substrates produced from water hyacinth, which were subjected to various pretreatments: the removal of microorganisms, moisture adjustment and selection of the parts of the plant to be treated. After inoculation the samples were kept in a spawning chamber at 25 °C and humidity of 70–80% to promote the growth of the fungus. After micellar invasion, treatments were kept in a light chamber between 20 and 25 °C for further fruiting. The fungus fructified in two substrates, wet and sterilized water hyacinth and wet water hyacinth, which were precomposed and pasteurized with roots; the first showed the best yields and a biological efficiency of 310.44% ± 85.27. The moisture-retention capacity and high levels of cellulose and hemicellulose in water hyacinth make it an excellent substrate and complement for other ones.

4. Biochar as soil substrate

Biochar is a porous carbonaceous material produced through thermochemical processes such as pyrolysis, gasification, torrefaction and hydrothermal carbonization. It can be used for heat and power generation, pollutant adsorption, and in agricultural, livestock and metallurgical applications [202,203]. In Mexico, several undervalued wastes, including water hyacinth, have been identified as suitable raw materials for biochar production [204].

Currently, pyrolysis is the most widely used methodology for the synthesis of biochar from *E. crassipes* biomass in Mexico. Jardón-Medina & Ortiz-Fernández [205] synthesized and evaluated biochar from water hyacinth, executing a total of 36 experimental tests, which included drying pretreatment until reaching a moisture content of 17–23%. The pyrolysis was performed at temperatures of 170, 200 and 230 °C and residence times of 120, 150, 180 and 210 min. The best biochar yield (76%) was found at a temperature of 170 °C and a residence time of 171.8 min, presenting a calorific value of 17.56 MJ/kg, which implies its potential use as solid biofuel. In addition to its energetic applications, water hyacinth-derived biochar has also been reported as an effective soil amendment due to its high porosity, nutrient content and water-retention capacity, improving soil aeration and pH while reducing nutrient leaching and enhancing fertility. It is well-known that biochar

is potentially a low-cost and environmentally friendly adsorbent [206]. In the study of Núñez Balderas et al. [207], water hyacinth-derived biochar was synthesized by pyrolysis at 600 °C and a residence time of 30 min. The results showed that biochar was highly effective in reducing the solubility of Zn and Cu and neutralizing pH. However, it was proven that the process of hydrothermal carbonization might seem a better option to produce biochar, because this obtained a carbonaceous material with a higher H/C ratio and lower aromaticity, releasing CO_2 and CH_4. Vázquez Mendoza [208] synthesized water hyacinth hydrocarbonate in order to use it in the removal of Cd (III) via hydrothermal treatment, evaluating the addition of citric acid to the hydrocarbonate to increase the adsorption of the pollutant. González-García et al. [209] synthesized activated carbon from the stems of the aquatic plant *Eichhornia crassipes* through chemical activation with potassium carbonate (K_2CO_3). The effects of impregnation time and activation temperature on the material's microstructure were analyzed, with optimal conditions at 800 °C and 24 h of impregnation. The resulting activated carbon exhibited a high specific surface area (~1132 m^2/g) and achieved a maximum adsorption capacity of 77.44% for sodium naproxen, demonstrating its potential as a sustainable adsorbent for pharmaceutical contaminated wastewater. In general, these uses add value to the plant while maintaining low environmental impacts and low operating costs.

Development of Materials

1. Water hyacinth fibers

One of the most viable options for the sustainable use of water hyacinth is through the synthesis of fibers, which can be used in the field of phytoremediation. The synthesis of fibers from water hyacinth in Mexico has been addressed for the removal of pollutants, emphasizing the removal of heavy metals. Granillo Suárez [210] established workshops for the elaboration of fibers and their artisanal handling, using water hyacinth fibers as a substitute for construction materials. Then, to obtain socio-economic benefits for artisans, David-Miros [211] implemented a business plan to benefit the residents of the Ojoxapan community (located in the municipality of Mecayapan, southern Veracruz), who make crafts from water hyacinth. Granillo Suárez [212] used a Solidarity Economy approach to analyze the production chain of handicrafts made from water hyacinths in the state of Veracruz, with the aim of obtaining a strengthening action plan to identify improvements and optimize processing. Ortiz & Linares [213] produced water hyacinth fibers through a static drainage pretreatment and natural drying over a period of 48 hr, crushing and washing them with a chlorine solution. The fibers were used in semi-hydroponic crops of beans and lettuce; the germination percentage was maintained between 90 and 95% for both crops.

The manufacture of tiles from paper and water hyacinth fibers with PET coatings was investigated by Muñoz-Hernández et al. [214]. The results showed that the PET coating improves permeability and mechanical strength, and can withstand up to 4.6 kg of load without fracturing. In other work, Paredo Sotelo et al. [215] analyzed fibers from water hyacinth using stereoscopic microscopy for the study of Pb removal. During their study, they worked at three Pb concentrations, 0.01, 0.5 and 2 mg/L, and obtained optimal removal results of ±98.18% and ±97.76% at concentrations of 0.01 and 0.5 mg/L, respectively. In the same year, Cuellar Mozqueda et al. [216] studied the removal of As using water hyacinth. The procedure was biomass dehydration as a pretreatment at 50 °C for 48 h to obtain the fibers (3 g of biomass), before washing them; then, to achieve a fibrous consistency, the biomass was placed inside a stove at 40 °C for 24 h. According to the results, the highest removal percentage was 4.58%, obtained for an As concentration of 25 µg/L, which indicates that the removal of As with fibers was not feasible. Chacón Guzmán et al. [217]

synthesized fibers from water hyacinth for the study of F removal at three experimental removal times of 1, 2 and 4 h; the maximum removal average achieved was 84.23 + 3.65% in the 0.5 mg/L solution. Cr removal in aqueous solutions from fiber synthesis was studied by Acosta et al. [218]. The Cr concentrations used were 0.01, 0.5 and 1 ppm; the highest removal of Cr was obtained at 1 mg/L with 81.2 + 4.07%. Medina et al. [219] carried out a feasibility analysis for the removal of Hg using water hyacinth, achieving 99% removal. As a material that requires less energy expenditure for its production compared to synthetic fibers, water hyacinth fibers can be used in different areas. It is important to note that water hyacinth fiber has the ability to absorb 2.5 to 4 times its weight in liquid [220]; therefore, it is a viable option for a wide range of uses. Future perspectives in this area should investigate and optimize the synthesis of this type of biomaterials from water hyacinth to avoid problems associated with the demand for aquatic resources.

2. Biocomposites

The growing societal commitment to environmental protection has intensified the search for biobased materials. A biocomposite consists of a polymer resin reinforced with natural fibers, which enhance its thermal and mechanical properties and reduce the resin degradation service life [221]. Quijano & López [222] described the usefulness of using *E. crassipes* fibers for the production of bio-composites, proposing mixing the fibers with other materials, such as earth, clay, sand, plastics and stone floors, for the construction of durable and high-quality adobes. Their experimental results showed that the material obtained had good cohesion and good thermal and acoustic insulation properties, as well as a good humidity regulation capacity, highlighting its potential as a biodegradable and sustainable construction alternative. González [223] carried out an exploratory experimentation on biobases and the sustainable processing of water hyacinth fibers for the development of optimal formulations for the production of bio-composites, which could be used in the manufacture of objects with sustainable design. The formulations all obtained seven different presentations of fiber and biobases, which were combined and laminated. The formula of the optimal matrix was: water 30 g, starch 7.5 g, vinegar 7.5 g, and glycerin 7.5 g, with 1.5 g of dry fiber, gelatin bioplastic vinyl and starch with water hyacinth fiber. Camacho Martínez [162] produced bio-composites from water hyacinth with a polyester matrix through mechanical reforming processes for their use in sustainable building materials. According to the physical–mechanical tests carried out on the materials, the 50% water hyacinth–50% binder mixture showed adequate dimensional stability and a greater resistance to compression and bending of 1.26 y 0.73 MPa. Additionally, the insertion of the plant in the mixture improves the cohesion of the material. The incorporation of plant fibers enhanced the cohesion and uniformity of the composite, resulting in a lightweight and resistant material suitable for non-structural construction components such as panels and insulation boards. The study demonstrated that the use of *Eichhornia crassipes* fibers can contribute to the development of eco-efficient building materials with reduced environmental impact.

As thermoset resins, such as polyester, have good dimensional and thermal stability and chemical resistance, they are now used in a wide range of applications, acting as the matrix of a composite material [224]. Flores Ramirez et al. [225] synthesized bio-composites based on polyester and water hyacinth fibers, varying the concentration of the fibers; the best results depended on mechanical properties such as deformation and resistance. The best mechanical performance, in terms of deformation and resistance, was observed in composites containing 5–10% by weight of water hyacinth fiber. Regarding moisture behavior, the study found that the hydrophilic nature of the fiber was responsible for water and humidity absorption. Notably, the composite containing 20% water hyacinth fiber exhibited the highest water and moisture absorption, reaching 24.03% and 6.13%, respectively.

3. Structuring agent

The efficient use of moist, low-cellulose biomasses and bio-residues for producing high-value products such as compost or biogas requires structuring agents that enhance aeration in bioprocesses [226]. Ideally, these agents form a three-dimensional matrix capable of supporting itself and creating pores that facilitate airflow and regulate moisture within the waste mixture. Water hyacinth has proven to be effective as a structuring agent for improving composting conditions [227]. Water hyacinth has been proven to have potential as an effective structuring agent to improve composting conditions [228]. Ramírez-Sánchez et al. [226] used it in a mixture with wood chips for aerobic treatments of heterogeneous organic waste at different percentages; the best results were obtained when used at a rate of 15% in the structuring agent, which improved the texture of waste piles, avoiding anaerobiosis conditions and allowing got adequate leachate absorption. In the study carried out by Angel-Cuapio et al. [229] water hyacinth was evaluated as a texturizing agent for increasing the porosity fraction, favoring gas exchange during the production of conidia from the fungus *Isaria fumosorosea*. The substrate used was a mixture of rice and water hyacinth at proportions 90–10% and 80–20%. The mixture of rice and water hyacinth that was obtained improved the conidia yields by 1.33 and 1.55 times compared to rice. The use of water hyacinth in the structure improves the biochemical processes of biomass transformation.

4. Eco-Friendly Paper

The polymer industry remains one of the most significant sectors of the global economy due to the persistent demand for its products across technological applications [230]. However, the environmental impact of polymer production [its greenhouse gas emissions and long degradation times] has driven the development of more sustainable materials, such as eco-friendly paper. This category of biomaterials includes nanometric cellulosic materials characterized by excellent mechanical, thermal and electrical properties. This section presents studies on eco-friendly paper produced from *Eichhornia crassipes* in Mexico [231–236].

The production of ecological paper involves mechanical operations beginning with biomass crushing, followed by beating to obtain a coarse pulp. The pulp is then processed manually by placing it on racks and applying mechanical pressure to remove moisture. Finally, it is sun-dried for about two hours. Ecological paper shows promising market potential, with a 60% acceptance rate among the population [233]. In the same sense, related to the artisanal co-processing of ecological paper from water hyacinth, this ecotechnology is currently used in lake areas where water hyacinth is highly distributed, providing a solution to its infestation, improving the environment, and taking advantage of the high availability of this biomass [231].

Nanocellulose can also be used to produce sophisticated paper using biomass, such as water hyacinth. Nanocellulose has been studied due to its wide range of physical and chemical characteristics, wide range of attributes, such as biocompatibility, recyclability and a low risk of toxicity, the economic feasibility of its production and its functionality. Gaytán-Lara [232] studied the optimized synthesis of nanocellulose using water hyacinth. The optimization was based on the use of lower acid concentrations, comparing the properties of the nanomaterial obtained with commercial nanocellulose. The samples obtained were characterized by X-ray diffraction, Fourier Transform Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR) techniques. The results showed that the isolation of nanocellulose was successfully achieved.

Cellulose nanofibers obtained using cellulose fibers from lignocellulosic materials, have been characterized with respect to their behavior under temperature variations and high resistance, allowing for a range of diverse applications [237]. In the same sense, in the study carried out by Ramos-Vargas et al. [238], the Kraft Pulp Process was used to synthesize

an adsorbent from water hyacinth, called cellulose nanofibers (NFC), with the aim of using them for the removal of Pb (II) ions from aqueous solutions, demonstrating the biosorbent's potential to eliminate this contaminant. The nanofibers were characterized using FTIR, Transmission Electron Microscopy (TEM), and Scanning Electron Microscopy (SEM) to evaluate their chemical structure and morphological features. According to the results, maximum adsorption capacities of 80.02, 84.64 and 87.10 mg/g for NFC were obtained at 25, 30 and 45 °C, respectively; also, the characterization showed excellent structural properties and high availability of functional groups. Arenas et al. [239] produced bioadsorbents for use in the purification of biodiesel from various organic wastes, including water hyacinth. The use of the adsorbent allowed for a 47.5% reduction in the biodiesel acidity index.

The synthesis of pulp from water hyacinth has been addressed by Pintor-Ibarra [234] and Pintor-Ibarra et al. [235]. In both studies, cellulosic pulp was obtained by the Kraft process, with cooking performed in a conventional digester at temperatures between 120 and 150 °C for 10 to 30 min. After cooking, the pulp was washed and filtered. The pulp yields, defined as the percentage of pulp obtained with respect to the initial dry biomass used, were 25.34% with a 10% reagent load in the first study, and 26.4% under similar conditions in the second. These values indicate the technical viability of the plant as a raw material for cellulose production.

5. Lignin

Recent research on the chemical and biochemical transformation of agricultural, agro-industrial, urban and lignocellulosic residues into high-value products has highlighted the role of lignin because its removal is essential for achieving good yields in processes such as biofuel production. Although often treated as a by-product, lignin has multiple applications, including resin synthesis, natural adhesives, carbon-fiber production and energy generation [240–243]. Water hyacinth, being abundant and rich in polymers, has been explored as a lignin source for bioproduct generation [53,244]. However, in Mexico, studies on the extraction and characterization of lignin from this plant remain scarce and poorly documented. Espinoza-Acosta et al. [245] studied the potential of water hyacinth as a source of lignin, evaluating the antioxidant activity present by stabilizing DPPH (2,2-diphenyl-1-picrylhydrazil) and ABTS (2,2'-azino-bis(3-ethylbenzenzothiazolin)-6-sulfonic free radicals). The extraction of lignin was carried out using the organosolv technique, in which the lignin polymer is fragmented into small dimensions, dissolving the biomass and separating it in the form of a liquor enriched in phenolic compounds. The process begins by hydrolyzing the biomass with a mixture of acetic acid (AA), formic acid (FC) and distilled water (DW) (AA/FC/DW 60:30:10 $v/v/v$ ratio 1:10 w/v) for 4 h; then, the sample is filtered, and, in the liquid phase (lignin + hemicellulose), hemicellulose is precipitated using 95% ethanol to obtain ethanol-soluble lignin, which is finally evaporated. The extraction results showed a yield of 15.2%, while spectroscopy identified conventional vibrations of chemical structures of the extracted lignin, in addition to an excellent temperature-resistance property (500–800 °C).

3.2.5. Level 4: Energy [Biofuels, Heat Production and Electricity Generation]

Fermentable Sugars and Bioethanol

The production of bioalcohols from lignocellulosic biomass such as water hyacinth is a promising alternative to fossil fuels, as the plant is abundant, does not compete with food production, and contains high hemicellulose (48%) and low lignin (3%) contents. In Mexico, several studies have examined bioethanol production from this biomass, addressing pretreatment methods and fermentation processes [246,247]. A study of biomass preparations for the production of bioethanol was conducted by López-Ramírez et al. [248]. They studied the effect of two thermal pretreatments to carry out the acid hydrolysis of water hyacinth; the pretreatments consisted of steam explosion and a bath with hot boiling

water. The methodology used was as follows: the collected biomass was separated into leaves, stem and root; once fractionated, they were taken to a dryer at 60 °C for 24 h for the steam explosion pretreatment, and then the samples were placed inside an autoclave at 120 °C and 1 atm pressure for 30 min, and finally, the samples were neutralized. The pretreatment of a bath with boiling water consisted of a boiling water bath for 30 min at 92 °C and 0.77 atm. After the pretreatments were applied, the quantification of sugars was carried out. Their results showed that through the addition of acid and the explosion of vapor, it was possible to release 324.26 ± 13.4 mg/g of initial dry matter, which translated into an increase of up to 26 times more compared to the samples treated with acid without the pretreatment, where only 6.9 and 12.5 mg/g were released. Regarding the samples treated using a bath with boiling water, the trend indicated that time has a linear impact on the increase in the release of reducing sugars; thus, the maximum time was 30 min, which achieved the best values. Likewise, in the study carried out by López Sánchez [249], hydrolysis pretreatments in an autoclave and in a microwave reactor were compared to verify the opening of the lignocellulosic matrix. The optimal hydrolysis conditions for both pretreatments were an operating time of 30 min and temperature of 120 °C. The residue was taken to enzymatic digestion, showing the highest yields in the solid remnant.

In the study of Espejel-Pérez & Mireles-López [250], biomass from water hyacinth was treated with 95.98% sulfuric acid in constant agitation and subjected to hydrolysis reactions for its subsequent fermentation for bioethanol production, using the strain Saccharomyces cerevisiae for 40 h at 28 °C. The distillation of the fermented product was performed at 78 °C to separate the ethanol. The process achieved an average yield of 0.43 g of ethanol per gram of dry biomass (~43%), demonstrating the plant's potential as a viable lignocellulosic substrate for bioethanol production under acidic hydrolysis conditions. The process resulted in a bioethanol production of 9.4 mL per 100 g of dry water hyacinth, demonstrating the potential of this aquatic plant as a substrate for second-generation biofuel production.

Figueroa- Torres et al. [247] studied and evaluated bioethanol production using steam explosion as a pretreatment, at 190 °C, with retention times of 1, 5 and 10 min, as well as enzymatic saccharification using hydrolytic enzymes produced by solid-state fermentation (SSF) and water hyacinth as the substrate. They used *Trichoderma harzianum* as an inoculum for the production of cellulase and xylase by SSF, and Saccharomyces cerevisiae as an inoculum in alcoholic fermentation. Also, it is worth noting that, to support the production of xylase and cellulase, they used columns of a packed bed at a temperature of 30 °C, supplied with oxygen by aeration (50 mL/min). The results showed that the the maximum concentration of reduced sugars was 15.5 g/L, the efficiency in enzymatic hydrolysis was 0.51 g of reduced sugars per gram of water hyacinth, and the maximum ethanol concentration achieved was 7.13 g/L, with a yield of 0.23 g of ethanol per g of dry matter. In another work presented by Landa Fernández [246], ethanol was produced from water hyacinth leaves and stems by enzymatic hydrolysis, with Trichoderma reesei cellulases followed by fermentation of reduced sugars by Zymomonas mobilis. The process yielded a maximum of 12.5 mL of ethanol per 100 g of dry water hyacinth, confirming the feasibility of this lignocellulosic biomass for bioethanol production.

Power Generation

Rising energy demand, declining fuel reserves, and increasing CO_2 and greenhouse gas emissions have accelerated the adoption of renewable and non-conventional energy sources [251]. For emerging countries, these alternatives offer promising pathways for energy access. Plant-based microbial fuel cells (CCMBPs) are one such technology, using microorganisms to convert chemical energy into electricity by transferring metabolically generated electrons to an electrode instead of a natural electron acceptor [252]. Water

hyacinth has been used in CCMBP prototypes, demonstrating the potential of these systems to generate electrical energy with a more favorable cost–production ratio compared to other developing technologies [253,254].

The implementation of projects with a sustainability focus has been proposed within rural communities in Mexico, with the aim of achieving the rapid and efficient recovery of water resources, preventing the deterioration of water bodies, and promoting energy generation. González Arévalo [255] proposed the implementation of water hyacinth collection projects to achieve a sustainable framework, seeking to avoid the continued deterioration of the Yuriria Lagoon in the state of Guanajuato. The proposed projects included the construction of wastewater treatment plants using water hyacinth, as well as the generation of electricity through the biogas produced. Although the study did not provide quantitative results, it emphasized the potential of integrating water hyacinth management with renewable energy generation as a strategy to mitigate organic pollution and promote environmental sustainability in the Yuriria Lagoon and the surrounding ecosystems.

Methane

Bioenergy from renewable resources is a viable alternative to fossil fuels, but meeting global energy demand requires ensuring the availability of renewable raw materials. Lignocellulosic biomass, which is abundant and widely accessible, is considered an optimal substrate for bioenergy production, particularly biogas [256–259]. Biogas is a clean, flammable biofuel composed mainly of CH_4 (50–70%), CO_2 (20–40%), trace gases such as NH_3, H_2S, CO, N_2, and O_2, and water vapor. It is produced through anaerobic digestion, a microbial degradation process involving four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [258]. A major advantage of biogas production is its ability to utilize diverse waste substrates, including livestock, agroindustrial and municipal residues, as well as sludge from wastewater treatment plants [256]. In Mexico, water hyacinth has been used as potential raw material in the production of biogas due to its content of essential nutrients, nitrogen, carbohydrates and cellulose; then, it is hydrolyzed into glucose through the action of microorganisms and/or bacteria to produce biogas.

Jacuinde Ruíz [260] evaluated the increase in the production of methane content in a biogas produced by applying and combining pretreatments, such as grinding, and modifying operating variables, such as pH, temperature control and concentration control, during the digestion process. Their results showed that the combined pretreatment had positive effects on methane production, in contrast to untreated biomass, with the optimal operating conditions being pH = 8.5, temperature = 40 °C, and a concentration of 30 g COD/L for a time of 30 min. This allowed for a production increase of 260% with respect to the kinetic constant of CH_4 production, which was 0.17/day, equivalent to 0.028 kg CH_4/kg of water hyacinth. Romero De León et al. [261] investigated the digestion feasibility and anaerobic co-digestion in the treatment of organic waste for the production of biogas, determining the biochemical potential of methane from water hyacinth and urban solid waste. The experiments were carried out under thermophilic conditions (55 °C), with hydraulic retention times of 50 days and two substrate/inoculum ratios.

3.2.6. Structural and Compositional Analysis of Water Hyacinth Biomass

Material characterization techniques allow for the study of morphological and functional properties to obtain the relevant information [such as mechanical strength and thermal stability] needed to evaluate a material's feasibility for specific applications [262]. In biomass research, compositional analysis is the first step in determining thermodynamic behavior, defining technological pathways, and addressing environmental issues related to a material's use as a bioproduct or biofuel [263]. Current studies on water hyacinth focus on

identifying conversion routes based on its composition [35,115]. Characterization research in Mexico has also examined the plant's variable chemical composition according to water body and maturity stage (young, medium, mature) [244,264]. Looking at the information collected, a classification was carried out related to the number of publications per year, as presented in Figure 7, with the highest number occurring between 2015 and 2016. Data regarding the variability of the composition as a function of the aquatic body is presented in Figure 8; it can be observed that the highest incidence is at Lake Xochimilco, with 17.5% of the total information obtained, followed by the Lerma River, with 11.8%.

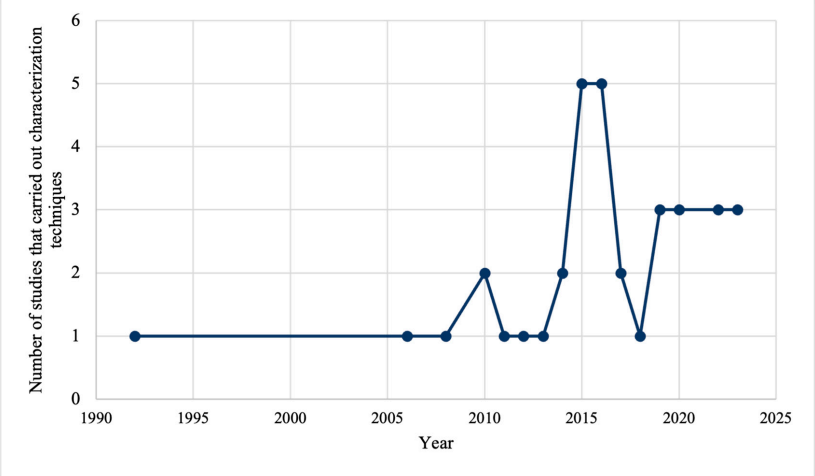

Figure 7. Studies that carried out water hyacinth characterization techniques.

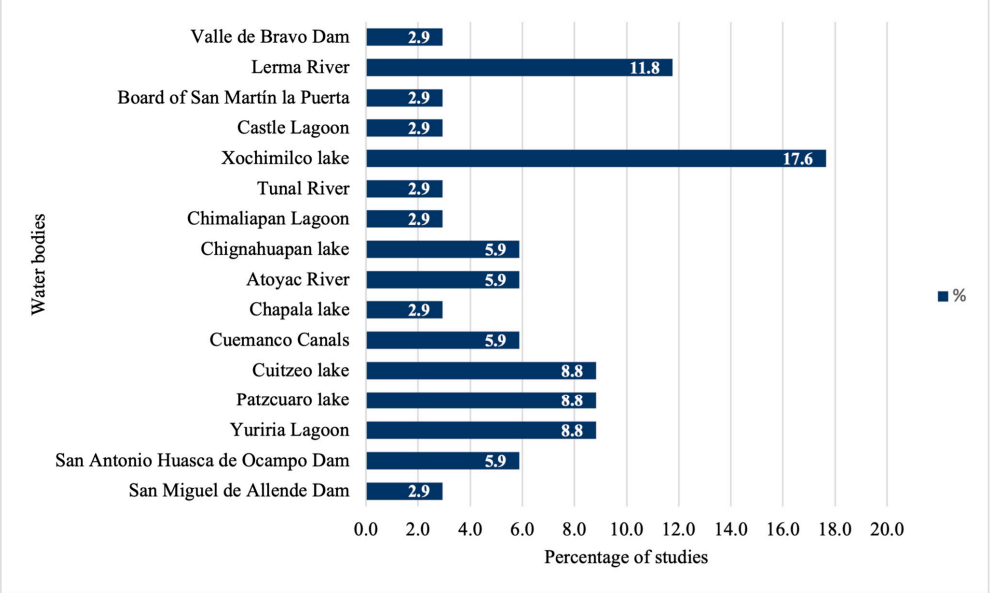

Figure 8. Water bodies from which water hyacinth samples were extracted to carry out characterization techniques.

Next, some characterization techniques reported for water hyacinth in Mexico are presented, such as morphological analysis, proximal analysis and elementary analysis.

Morphological Analysis

A morphological analysis of materials provides information about their shape, size and distribution, which are the morphological characteristics of materials, as well as the identification of their purity using microscopy techniques, images, optical microscopy and

scanning electron microscopy [265], with a focus on stereoscopic microscopy (SM) and SEM. The first is based on the use of reflected light to generate a three-dimensional visualization of the sample's surface at low magnifications, this technique allows for the observation of macroscopic features such as texture, color and overall morphology; the second one uses emitted electrons, the interaction between the electrons and the sample surface to generate signals such as secondary electrons, which are collected to produce high-resolution images of a detailed surface topology. Table 4 presents the reports on the morphological analysis of biomass and biomaterials from water hyacinth in Mexico.

Table 4. Synthesis of the morphological analyses of water hyacinth biomass in Mexico.

Technique	Analysis Results	Condition/Aquatic Body of Origin	References
SM	The observed particles had a porous texture, with shades ranging from yellow to brown, with irregular fibrous shapes. A shine was seen on its surface, indicating the presence of cellulose.	Guanajuato/NS	[217]
	The images provided showed that the fibers of the biomass vary in size and shape according to the grooves being observed.	Guanajuato/San Miguel de Allende Dam	[218]
	The observed particles had a porous texture, with shades ranging from yellow to brown, and each particle had irregular fibrous shapes.	Guanajuato/NS	[219]
	They determined that lignocellulosic fibers had a porous texture with irregular fibrous shapes. Also, they observed different colors ranging from yellow, green, to dark brown color. The presence of cellulose could also be observed due to a shine that stood out on the surface.	Guanajuato/NS	[216]
SEM	The analysis allowed for the observation of well-defined nanocellulose fibers with different sizes and some agglomeration of fibers. The grain size of the agglomerates for both bio-sorbents was approximately 0.5 mm; also, the diameter of the nanocellulose fiber was observed to be 97.9 nm.	Michoacán/Lake Cuitzeo	[238]
	The SEM of the water hyacinth made it possible to observe the morphological structure of nanofibers and cellulose that constituted the plant, as well as a cavernous structure that could be responsible for the adsorptive property of the solids.	NS	[266]
	The SEM results showed a brown coloration in the biomass; the surface was mostly porous, apparently with free spaces. A porous structure can result in large surfaces.	State of Mexico/ Lerma River	[267]

Note: NS means unspecified.

Proximal Analysis

Proximal analysis is defined as a chemical analysis scheme to determine the composition of a substance based on its thick components, such as moisture, mineral matter or ash, crude fat (ethereal extract), crude protein, crude fiber, and soluble carbohydrates [268–270]. In the case of water hyacinth, the techniques employed for the determination of moisture and ash contents included Ash Quantification Method No. 923.03 of the Official Association of Analytical Chemists (AOAC) [36,271–273], ASTM D2866-94 Standard Test Method for Total Ash Content of Activated Carbon" [209], TAPPI Standard Method T-211 om-93 for the determination of ash content [264], Mexican Standard NMX-AA-018-1984, which establishes the test methods used for the determination of ash from municipal solid waste [201], and the incineration method [274]. Table 5 presents the results of the proximal analysis, specifically the moisture and ash content of water hyacinth collected from different aquatic bodies in Mexico. These parameters are relevant for processing because moisture content strongly affects handling, storage stability, and the need for pre-drying prior to most thermochemical routes, while ash content represents the mineral fraction that can influence conversion performance and downstream management (e.g., mineral residues). The data also indicate that moisture and ash may vary by plant organ (P, L, S, R) and by water body

of origin, underscoring the importance of site- and organ-specific characterization when selecting and scaling valorization pathways.

Table 5. Proximal analysis of water hyacinth biomass in Mexico.

Ashes [%]				Moisture %				Condition/Aquatic Body of Origin	Reference
P	L	S	R	P	L	S	R		
-	12.09 ± 0.20	20.22 ± 0.29	-	-	-	-	-	Hidalgo/San Antonio Huasca de Ocampo Dam	[36]
-	13.5	20.2	27.6	-	82.3	92.2	91.8	Guanajuato/Yuriria Lagoon	[271]
-	20.57 ± 2.75		-	-	91.93 ± 0.1		-	Veracruz/Laguna el Castillo	[272]
18.31 ± 0.02	14.93 ± 0.01	21.21 ± 0.31	18.55 ± 0.65	-	-	-	-	Mexico City/ Lake Xochimilco	[273]
-	-	16.94	-	99.5	-	-	-	N/A	[209]
17.2	17.56	-	-	-	-	-	-	Hidalgo/San Antonio Dam	[264]
16.5	16.16	-	-	-	-	-	-	Mexico City/ Cuemanco Pier	
11.2	-	-	-	-	-	-	-	Jalisco/Lake Chapala	
20.3	16	-	-	-	-	-	-	Tabasco/N/S	
-	19.9 ± 0.25	26.8 ± 0.39	26.0 ± 0.22	-	-	-	-	Durango/El Tunal River	[244]
-	12.4 ± 0.04	14.4 ± 0.03	14.6 ± 0.09	-	-	-	-	Guanajuato/Yuriria Lagoon	
18.53 ± 0.82	10.21 ± 0.25		-	94.94 ± 0.22	92.70 ± 1.33		-	Mexico City/ Lake Xochimilco	[201]
19.65 ± 0.32	-	-	-	-	-	-	-	Mexico City/ Lake Xochimilco	[274]
19.37 ± 0.12	14.37 ± 0.29	20.78 ± 0.26	19.02 ± 0.12	92.7 ± 0.62	85.34 ± 0.34	93.61 ± 0.23	92.71 ± 0.34	Michoacán/ Lake Cuitzeo	[275]
-	13.87–13.28–11.47	21.13–24.71–18.08	-	-	-	-	-	Mexico City/Lake Xochimilco	[276]
-	-	-	-	94.9	-	-	-	State of Mexico/Valle de Bravo Dam	[277]

Note: P means plant, L means leaf, S means stem, and R means root.

Structural Analysis

Structural analyses of biomass provide crucial information to understand the composition and organization of components in the plant's cell wall, which is essential for the development of biotechnology applications, bioenergy and sustainable materials. The components determined via structural analysis are holocellulose, cellulose, hemicellulose and lignin. The techniques most frequently used for this analysis were the TAPPI standard quantification of holocellulose (T 211 om-93, 1993), cellulose (T 212 om-12, 2015), α and β-cellulose (T 203 cm-99, 2015) [36]; determination of the content of neutral amylase-treated detergent fiber (NDF) [209]; Technical Association of Pulp and Paper Industry (TAPPI) Standard Method T-222 om-88 acid-insoluble lignin in wood and pulp [264]; Runkel & Wilke's (1951) Method for Determination and ASTM D1103-60 (1981) Test Method for Alpha-Cellulose in Wood [244]; and FTIR [274]. Table 6 summarizes the structural composition of *Eichhornia crassipes* reported in different aquatic bodies in Mexico. Overall, the Mexican literature reports wide variability in the structural fractions of *Eichhornia crassipes* depending on the sampled plant organ (P, L, S, R) and the aquatic body of origin. Across the compiled studies, cellulose and hemicellulose contents span broad ranges (approximately 8–43% and 3–49%, respectively), while lignin values are also variable (about 4–26%), reflecting differences in sampling and reporting approaches. Despite this dispersion, the consistent presence of structural carbohydrates supports the feasibility of conversion routes aimed at fermentable sugars and bio-based materials, whereas the lignin fraction highlights the need for appropriate pretreatment when biochemical pathways are targeted.

Table 6. Synthesis of the structural analysis of water hyacinth biomass in Mexico.

Holocellulose [%]				Cellulose [%]			Hemicellulose [%]			Lignin [%]				Condition/Aquatic Body of Origin	Reference
P	L	S	R	L	S	R	L	S	R	P	L	S	R		
-	-	-	-	28.73 ± 9.41 (α-cellulose 25.82 ± 0.47, β-cellulose 1.77 ± 0.61)	42.67 ± 0.67 (α-cellulose 40.71 ± 0.37, β-cellulose 1.02 ± 0.22)	-	36.61	16.56	13.29	-	-	-	-	Hidalgo/San Antonio Huasca de Ocampo Dam	[36]
-	-	-	-	-	36.81	-	-	13.18	-	-	-	12.04	-	-	[209]
29.8	-	-	-	-	-	-	-	-	-	8.3	11	6	-	Hidalgo/San Antonio Dam	[264]
31.6	-	-	-	-	-	-	-	-	-	4.8	-	4.7	-	Mexico City/ Cuemanco Pier	
30.8	-	-	-	-	-	-	-	-	-	4.6	-	4.6	-	Jalisco/Lake Chapala	
30	-	-	-	-	-	-	-	-	-	5.5	-	-	-	Tabasco/NS	
-	17.1 ± 0.06	11.4 ± 0.50	23.7 ± 0.45	8.7 ± 0.76	8.4 ± 0.21	16.0 ± 0.77	8.4	3	7.7	-	11.5 ± 0.91	4.5 ± 0.08	13.4 ± 0.53	Durango/El Tunal River	[244]
-	36.8 ± 0.35	40.0 ± 0.34	43.4 ± 0.04	12.8 ± 0.30	14.2 ± 0.57	15.9 ± 0.45	24	25.8	27.5	-	14.3 ± 0.27	5.9 ± 0.18	8.8 ± 0.17	Guanajuato/Yuriria Lagoon	
34.21 ± 0.19	26.78 ± 0.07	37.17 ± 0.76	32.94 ± 1.17	-	-	-	-	-	-	19.95 ± 0.74	25.70 ± 1.55	12.54 ± 0.02	22.64 ± 0.8	Michoacán/Lake Cuitzeo	[275]
-	-	-	-	22.38 ± 1.37			23.44 ± 0.18			19.41 ± 1.79 [acid lignin]		7.62 ± 2.11 [alkaline lignin]		Mexico City/ Lake Xochimilco	[274]
-	-	-	-	21.5–17.8–18.2–21.1			33.9–43.4–48.7–25.9			-		6.0–7.8–3.5–12		Mexico City/ Lake Xochimilco	[276]

Note: P means plant, L means leaf, S means stem, and R means root.Ultimate Analysis.

The final analysis allows for the total contents of carbon, hydrogen, nitrogen, oxygen, sulfur and phosphorus present in a wide range of samples of organic and inorganic nature to be determined [278]. For water hyacinth samples collected in Mexico, the most commonly used techniques included the LECO-628 Elemental Analyzer (LECO Corporation, St. Joseph, MI, USA), which operates on the principle of high-temperature combustion in an oxygen atmosphere followed by infrared and thermal conductivity detection to quantify elemental composition [260], and controlled vacuum scanning electron microscopy (MEB-LV) for morphological and compositional characterization [279]. In Table 7, the elemental composition reported for Mexican samples of *Eichhornia crassipes* shows a moderate carbon content (around 31–49%) and very low sulfur content (reported at ~0.11%), while nitrogen content ranged from roughly 2.1 to 2.9% depending on whether the whole plant or a specific fraction (e.g., rootless biomass) was analyzed. In practical terms, this supports its potential use in energy-related routes (with carbon as the main contributor), and the low sulfur values are a positive indicator for its use in thermochemical processing. At the same time, the differences among studies reinforce that the results should always be interpreted in light of the sampled fraction and origin.

Table 7. Ultimate analysis of water hyacinth biomass in Mexico.

C	H	O	N	S	P	References
31.00% ± 0.03	5.20% ± 0.08	44.49% ± 1.63	2.10% ± 0.01	0.11% ± 0.01	0.32% ± 0.01	[260]
Entire floor: 44.18			Entire floor: 2.1 ± 0.19			[201]
Rootless plant: 48.37			Rootless plant: 2.90 ± 0.12			
49.22%	-	39.67%	-	-		[280]

Note: C means carbon, H means hydrogen, N means nitrogen, S means sulfur and P means phosphor.

The characterization of water hyacinth biomass is essential to unlock its potential as a renewable and sustainable resource. By understanding its physical, chemical and structural properties, it is possible to develop more efficient and cost-effective conversion processes for use in the production of bioenergy and green building materials, as well as high-value chemicals. A detailed characterization not only provides invaluable information for process optimization, but also allows the environmental impact of its use to be evaluated and improved strategies to be designed for its sustainable management.

4. Conclusions

The present study offers a systematic review of the literature that contributed to the understanding of strategies for water hyacinth valorization in Mexico, integrating biomass exploitation approaches and methods for controlling its proliferation and infestation. In this sense, the presented research provides an overview of the current scientific, technological and governmental efforts, as well as the identifying emerging opportunities for the comprehensive and sustainable use of water hyacinth, by classifying and organizing the uses and production of bio-products from its biomass and integrating them into the biomass recovery pyramid. Likewise, the geographical distribution related to extraction is provided, with the aim of identifying unexplored exploitation sectors. Based on the research questions raised, the following conclusions were drawn:

- Historically, Mexico has applied three main approaches to control and eradicate water hyacinth: biological, physical, and chemical. Most of the reviewed literature reports on biological control, mainly through the introduction of natural enemies such as *Neochetina bruchi* and *N. eichhorniae*. However, because biological control acts slowly, many programs have relied on physical methods [e.g., extraction, cutting, and in situ crushing], and chemical control has also been used, although less frequently, likely

due to the environmental and social impacts associated with herbicide application. Cases of comprehensive control methods have also been reported, combining physical, biological and, to a lesser extent, chemical approaches; however, current efforts have focused mainly on physical control, implemented using mechanical harvesters and crushers, as the predominant strategy in water bodies that present with infestation (E-1, E-2).

- Based on the literature review, it was identified that although water hyacinth is present and distributed in the majority of Mexican territories, studies on eradication actions were performed in only 10 states of the Republic and Mexico City. Sinaloa hosted the largest number of interventions, with 17.24%, followed by Mexico City, with 13.79%, while Puebla, Hidalgo and Jalisco represented 10.34%, and Guanajuato, Morelos, Nayarit, Veracruz and Michoacán registered 6.9% each; finally, Sonora reported 3.45% of the total. This pattern shows that although water hyacinth distribution is predominant throughout Mexico, documented eradication efforts have only been concentrated in certain regions. This suggests the existence of geographical gaps in the implementation and documentation of management strategies for contaminated water bodies (E-3).
- Regarding the approach to its use and exploitation, it was identified that 70.7% of the studies concentrated on level 3, "Chemicals and Materials", oriented toward the development of bioproducts focused on the treatment and remediation of water and soils, such as absorbers, biosorbents, biofilters and biochar, with applications in the agricultural and fertilizer sector, through the production of compost and vermicompost, as well as the use of the plant as a substrate and the development of materials such as fibers and bicomposites.
- In terms of level 4, "Energy", it was identified that 12.2% of the studies are oriented toward energy-recovery pathways, focused on the production of bioethanol, methane, and power generation, which positions this level as a relevant route for handling large biomass volumes through consolidated conversion approaches.
- With respect to level 1, "Health and Lifestyle", it was identified that 9.8% of the studies are oriented towards higher-value applications, using the plant as a source of bioactive extracts, as well as in the synthesis of fructans and nanoparticles and the production of living organisms, which places this level as an emerging but still limited research area in the Mexican context.
- As for level 2, "Food (Food and Feed)", it was identified that only 7.3% of the studies are oriented towards applications in the production of feed and forage for the poultry and livestock sectors, which positions this level as one of the least explored areas and, therefore, as a potential line of opportunity, particularly if future work strengthens safety, quality control, and regulatory considerations.
- From a practical standpoint, the most beneficial pathway for environmental and economic sustainability is to prioritize scalable routes that can absorb large volumes of biomass and are compatible with the conditions of Mexican water bodies, using them as the backbone of management, while positioning Levels 1 and 2 as complementary, higher-value directions to be pursued selectively under stricter safety controls and regulatory compliance.
- A total of 72.3% of the studies explicitly report the Mexican state, as well as the water body from which the water hyacinth was extracted, while 27.7% do not provide such information. The largest concentration of studies was in Guanajuato, Michoacán, Veracruz and Estado de México, with a predominant orientation towards level 3, "Chemicals and Materials" (U-2).
- It is widely recommended to strengthen integrated management strategies in which the exploitation of biomass is promoted as part of the control, as well as stimulating

research directed towards the production of high-value products in sectors such as pharmaceuticals and fine chemicals.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr14050745/s1, Table S1. PRISMA 2020 Checklist [281].

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