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# Scientific and technological perspectives of the water lily (*Pontederia crassipes*): Innovative applications of its biomass

# Perspectivas científicas y tecnológicas del lirio acuático (*Pontederia crassipes*): Aplicaciones innovadoras de su biomasa

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## ABSTRACT

**Background.** The water lily (*Pontederia crassipes*), is considered globally as one of the most problematic invasive plants, with a high dissemination capacity and biological efficiency, enhancing significant environmental impacts in freshwater bodies. **Goals.** The present study provides a scientific and technological review of its phenology, dispersal mechanisms and innovative applications of its biomass. **Methods.** 100 articles from scientific and technological databases were analyzed, using a qualitative approach to evaluate technological surveillance, as well as intellectual property issues. The present review emphasizes *P. crassipes* impacts, predictions and effective strategies for the design of proper management and control. **Results.** As *P. crassipes* presents efficient mechanisms of dispersal and reproduction, a high viability of its seeds and their easy dispersal through currents, combined with human activities, its eradication is difficult. It was found that the greatest difficulty is the barriers that exist for its management. Logistical and financial challenges persist, especially in developing countries such as Mexico. Additionally, there is a lack of precise estimates on the economic costs and losses associated with the invasion of this plant. Therefore, a comprehensive review that integrates the most recent advances in these areas and provides a global vision of the current state of knowledge, as well as the opportunities and challenges that this species represents is needed. **Conclusions.** Overall, solid foundations for future research and public policies aimed at the sustainable management and use of the biomass of this plant will ensure a better approach.

**Keywords**: Eutrophication, invasive species, mitigation, patents, socioeconomic impact.

## RESUMEN

**Antecedentes.** El lirio acuático (*Pontederia crassipes*) es considerado a nivel global como una de las plantas invasoras más problemáticas, debido a su alta capacidad de diseminación y eficiencia biológica, lo que genera impactos ambientales significativos en cuerpos de agua dulce. **Objetivo.** El presente estudio ofrece una revisión científica y tecnológica sobre su fenología, mecanismos de dispersión y aplicaciones innovadoras de su biomasa. **Métodos**. Se analizaron 100 artículos provenientes de bases de datos científicas y tecnológicas, utilizando un enfoque cualitativo para evaluar la vigilancia tecnológica, así como aspectos relacionados con la propiedad intelectual. Esta revisión enfatiza sus impactos, posibles predicciones y estrategias efectivas para diseñar un manejo y control adecuado. **Resultados.** Dado que *P. crassipes* presenta mecanismos eficientes de dispersión y reproducción, alta viabilidad de sus semillas y su fácil propagación a través de corrientes, combinada con actividades humanas, su erradicación resulta difícil. Se identificó que la mayor dificultad radica en las barreras para su manejo. Persisten desafíos logísticos y financieros, especialmente en países en desarrollo como México. Además, existe una falta de estimaciones precisas sobre los costos económicos y las pérdidas asociadas con la invasión de esta planta. Por lo tanto, se requiere una revisión integral que integre los avances más recientes en estas áreas y que proporcione una visión global del estado actual del conocimiento, así como de las oportunidades y desafíos que esta especie representa. **Conclusiones**. En términos generales, establecer bases sólidas para investigaciones futuras y políticas públicas orientadas al manejo sostenible y uso de la biomasa de esta planta garantizará un enfoque más efectivo.

**Palabras clave:** Especies invasoras, eutrofización, impacto socioeconómico, mitigación, patentes.

## INTRODUCTION

The water hyacinth, *Pontederia crassipes* Mart. (Liliopsida), is a widely recognized ornamental plant that has become invasive due to its rapid proliferation, now prevalent in most tropical and subtropical freshwater ecosystems (figure 1) (Niño-Sulkowska & Lot, 1983; Coetzee & Hill, 2012; Flores-Rojas *et al.*, 2024). Native to South America, it was initially cultivated for its vibrant flowers, but its exceptional dispersal and reproductive abilities (both sexual and asexual) have enabled its expansion into aquatic habitats across warm-climate regions (Mathiventhan *et al.*, 2018; Rodríguez-Lara *et al.*, 2022). The species spreads rapidly through stolons, fragments, and seeds, which can remain viable for up to 20 years, challenging its eradication (Barrett & Forno, 1982; Ghoussein *et al.*, 2023). Additionally, its dispersal is favored by natural factors, such as water currents, and human activities, such as transport via boats (MITECO, 2019; Rodríguez-Lara *et al.*, 2022). These characteristics, combined with its morphological and phenological adaptability, have made *P. crassipes* a threat to biodiversity and the functionality of aquatic ecosystems, justifying the need for innovative strategies for its management and control. Despite its presence in all continents, most studies have been developed in countries such as Indonesia and Brazil (Gopalakrishnan *et al.*, 2011; Kamala-Bai *et al.*, 2023; Ghoussein *et al.*, 2023).

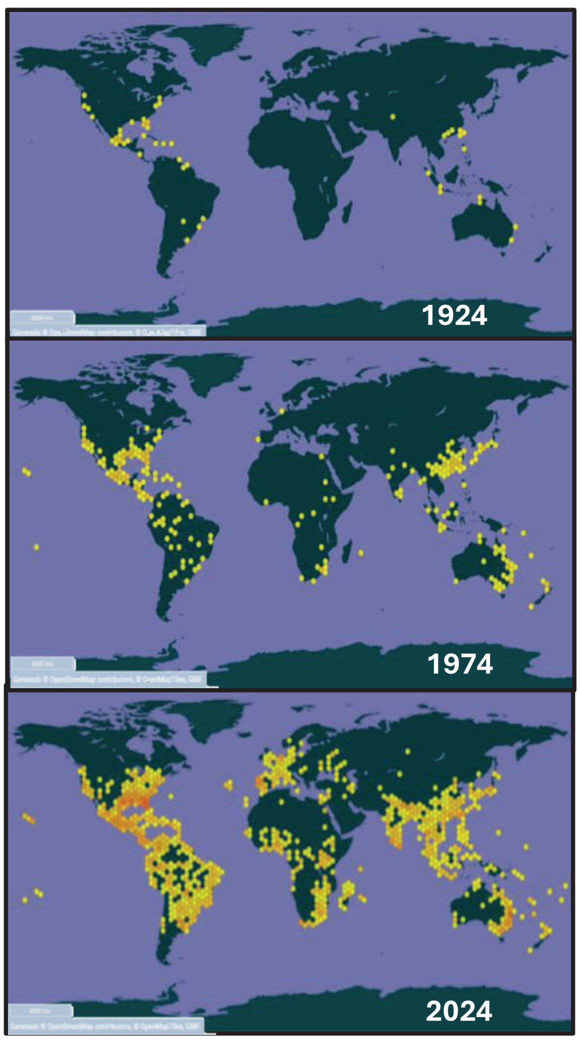


Fig. 1. Georeferenced records of *Pontederia crassipes* on a global scale. This figure illustrates the geographic distribution of presence records for the species across various years and regions worldwide. From GBIF.

Phenology and the spread mechanisms provide crucial information to understand the behavior of an invasive plant in an ecosystem, as this plant has a phenological cycle sensitive to climate, thus providing predictions on how climate change could facilitate its expansion or intensify its effects. The uncontrolled expansion of *P. crassipes* in freshwater bodies has significant environmental and economic impacts (Ayanda *et al.*, 2020; Kariyawasam *et al.*, 2021; Karouach *et al.*, 2022; Flores-Rojas *et al.*, 2024). Among the main documented effects are the reduction in light penetration in waterbodies, enhancing an increase in turbidity and acidity, therefore decreasing dissolved oxygen levels, and a proliferation of pathogens as a consequence (Mathiventhan *et al.*, 2018; Ghoussein *et al.*, 2023). These alterations not only affect the physicochemical characteristics of aquatic ecosystems but also promote eutrophication and compromise local biodiversity, displacing native species due to the water hyacinth's high adaptive capacity (Niño-Sulkowska & Lot, 1983; Shanab *et al.*, 2010). A significant gap in knowledge regarding the water lily (*P. crassipes*) lies in the lack of a systematic and updated integration of scientific and technological advances in its management, control and use. Although there are a significant number of studies focused on the environmental impacts of this invasive species, information about its management and potential use as biomass is usually fragmented and limited to local contexts or specific regions. Research on the potential applications of the water lily, such as its use in bioenergy, generation of bioproducts, and bioremediation capacity, has not yet been sufficiently compiled or even analyzed in a global manner to allow its economic and technical viability to be evaluated. Additionally, the lack of data and analysis makes it difficult to identify sustainable strategies and approaches for its management that not only mitigates its negative impacts, but also take advantage of its biomass for the benefit of scientific knowledge but mainly of the communities that suffer from this problem. The objective of the present review is to analyze and discuss the scientific and technological advances related to the management, impact, and possible applications of *P. crassipes* in continental waterbodies, as well as contribute to the identification of innovative strategies for its control and sustainable use.

## MATERIALS AND METHODS

The present assessment focused on an exhaustive review of existing knowledge in the available literature regarding the management, control, and utilization of *Pontederia crassipes* biomass. Particularly, aspects related to controlling its spread and exploring the potential uses of its biomass were addressed, aiming to provide a comprehensive perspective on the current situation of this invasive species while considering its environmental, social, and economic implications. Hence, specific keywords and phrases were proposed: control of water hyacinth propagation, uses, innovations in invasive species, management of *P. crassipes*, *Eichhornia crassipes* environmental impacts, sustainable utilization of water hyacinth, and economic implications of water hyacinth. When carrying out each search, we sought to alternate the use of the names *P. crassipes* and *E. crassipes*, due they are synonyms. For the selection of scientific articles, studies addressing aspects related to the phenology, dispersal, management, control, and innovative applications of the biomass of *P. crassipes* (= *E. crassipes*), published in scientific databases such as Science Direct, Springer Link, Elsevier, Academia, ResearchGate, and Wiley, were included. Priority was given to articles published in peer-reviewed journals, especially those providing relevant information on environmental impacts, socioeconomic effects, and technological applications of the species. Documents that were not available in full text, those that did not directly address the species in question, and studies lacking scientific rigor or empirical support were excluded. The study analyzed 100 articles sourced from six scientific and technological databases: Science Direct, Springer Link, Elsevier, Academia, ResearchGate, and Wiley, as well as resources such as Google Patents, Espacenet, and OEMP (Spanish Patent and Trademark Office). Concerning patents, records related to the use, management, or applications of *P. crassipes* in intellectual property databases such as Google Patents, Espacenet, and OEMP were included. Patents registered between 1983 and 2024 were considered, with a focus on those demonstrating technological innovations or practical applications of the species' biomass. Patents not directly related to *P. crassipes* or lacking detailed application information were excluded. For the review of technological surveillance, only the names *P. crassipes* and *E. crassipes* were used for searches in the technological information databases (Google Patents, Espacenet, and OEMP). The grouping of technological advances was conducted by exporting data from the patent databases. First, patents were classified by country code to identify regions with the highest innovative activity. Then, the analysis focused on Mexican patents, classifying them by their main areas of application: bioremediation, agricultural inputs, bioenergy, biomaterials, and pharmaceutical applications. Subsequently, each report was categorized by country code and year of publication. Thus, a qualitative approach was employed to assess global information on technological surveillance, particularly concentrating on America with an emphasis on Mexico. In line with the evaluation, the analysis included a breakdown by states and topics related to intellectual property protection.

## RESULTS

Regarding the data obtained in the various databases, the use of water hyacinth biomass has emerged as an effective alternative for managing this invasive plant, turning an ecological challenge into an economically and environmentally sustainable opportunity. Authors agree that controlled biomass harvesting not only helps reduce plant populations and prevent their spread but also minimizes ecological damage, such as biodiversity loss and water quality deterioration. Hence, in general, the approach offers a resource that can be harnessed for various industrial and commercial applications (Espinosa-García & Villaseñor, 2017).

Notably, the extracted biomass of *P. crassipes* has multiple applications, highlighting its potential use as a valuable resource. Production of bioplastics and other biodegradable products, wastewater treatment, energy generation, and biofuel production are some of the potential values of the biomass. Such initiatives not only diversify the plant management strategies but also promote the development of innovative and sustainable solutions (Pradhan *et al.*, 2017; Sierra-Carmona *et al.*, 2022). However, several technological and economic challenges hinder the large-scale implementation of these applications. For instance, the high moisture content of the biomass complicates its processing for biofuel production, while the variability in its chemical composition affects the consistency of bioplastics and other biomaterials (Carreño-Sayago & Rodríguez-Parra, 2018; Bakrim *et al.*, 2022). Additionally, the lack of cost-effective harvesting and processing technologies and limited infrastructure in developing countries pose significant economic barriers (Karouach *et al.*, 2022; Rodríguez-Lara *et al.*, 2022). Addressing these challenges through further research and technological innovation could optimize existing processes and unlock the full potential of *P. crassipes* biomass.

One of the most promising uses for water hyacinth biomass is the production of biopolymers. Plant components such as cellulose, $\beta$-glucosidase, and xylanase serve as substrates for the creation of compounds such as, polyhydroxybutyrate (PHB), a biopolymer with broad industrial and environmental applications. Studies have shown that enzymatic hydrolysis of this plant can yield up to 4.3 g/L of PHB using microorganisms in fermentation processes (Radhika & Murugesan, 2012; Bakrim *et al.*, 2022), highlighting the necessity for further promising studies.

Beyond industrial uses, water hyacinth has shown potential in the biomedical field. Ethanolic and methanolic extracts from its leaves have demonstrated analgesic, antimicrobial, antifungal, and neuroprotective properties. Likewise, previous research has reported effective inhibition zones against bacteria such as *Bacillus subtilis* (Ehrenberg 1835) Cohn 1872, and fungi like *Aspergillus niger* Tiegh., highlighting its utility in developing natural therapeutic and antibacterial agents (Shanab *et al.*, 2010; Sitoe & Van Wyk, 2024).

The species also shows promise in biofuel production due to its high hemicellulose content and volatile compounds. Previous assessments have reported the production of biogas, bioethanol, and biohydrogen, with estimated yields of up to 100 $Nm^3$/kg of biogas and 245 g/kg of bioethanol from its biomass. The associated technologies include thermochemical methods, biochemical processes, and direct combustion, demonstrating its versatility as a raw material for sustainable energy initiatives (Carreño-Sayago & Rodríguez-Parra, 2018; Pinho & Mateus, 2023).

Regarding technological monitoring, three patent databases, were used, emphasizing the use of Google Patents, which provided the most records. From the data obtained, a classification of patents by year was carried out, spanning from 1983 to November 2024. As observed in the data obtained (Fig. 2), this time frame captures the progressive trends and significant increases in patent activity, reflecting the growing interest and advancements in the field. The records in the literature compiled highlight notable peaks in patent registration, particularly in recent decades, suggesting accelerated innovation and technological developments. The temporal distribution also offers valuable insights regarding the periods of heightened activity, due to breakthroughs, regulatory changes, or shifts in market demand.

Globally, China leads in intellectual property related to water hyacinth utilization with more than 60% of patents. China's leadership in intellectual property related to *P. crassipes* can be attributed to its strong investment in research and development (R&D) and its strategic focus on leveraging invasive species for economic and environmental benefits. The country has implemented policies that promote innovation in biomass utilization, particularly in areas such as bioenergy, bioremediation, and biomaterials (Guo *et al.*, 2022). Additionally, China's large-scale infrastructure for processing aquatic biomass and its commitment to sustainable development have facilitated the rapid development and patenting of technologies related to *P. crassipes* (Lu *et al.*, 2007). This contrasts with other countries, where funding and infrastructure for such innovations are often limited. Following China, the United States plays a significant but smaller role, contributing 7% of the patents. The remaining contributions are distributed among other countries, each with varying levels of engagement in intellectual property protection related to the multiple uses of water hyacinth (fig. 3). In the Americas, the U.S. holds up to 84% of patents, with the remaining contributions divided among Brazil, Mexico, Canada, Chile, Colombia, and Portugal (fig. 4). Particularly, Mexico contributes with more than 8% of the patents, reflecting its growing but still limited participation in the regional innovation ecosystem. Mexico's limited participation in intellectual property related to *P. crassipes* can be attributed to several factors, including insufficient funding for R&D, limited infrastructure for biomass processing, and a lack of integrated policies that promote innovation in sustainable technologies (Espinosa-García & Villaseñor, 2017). Additionally, the focus on traditional management strategies, such as mechanical removal, has overshadowed the potential for technological innovation. To adapt technologies developed in other countries, Mexico could establish partnerships with leading nations like China and the United States, focusing on knowledge transfer and capacity building. Furthermore, government incentives for private-sector investment in R&D and establishing specialized research centers could foster innovation in bioremediation, bioenergy, and biomaterials (Rodríguez-Lara *et al.*, 2022).

For the present study, regarding Mexico, patent distribution related to *P. crassipes* was categorized by technological area and state. Mexico City leads with up to 57% of patents, followed by Sonora and Jalisco with 9% each. Meanwhile, states such as Baja California, Veracruz, Tabasco, Sinaloa, Guanajuato, and Coahuila contribute only 4%, respectively. Agro-inputs represent the area with the highest number of patents (8 records), reflecting interest in sustainable agriculture. Notably, bioremediation records account for up to 35% of patents, driven by states like Veracruz and Tabasco. Conversely, pharmaceuticals represent 15%, with significant contributions from states such as, Jalisco and Guanajuato. Despite the current interest in subjects such as biofuels, biocontrol, and biomaterials, the records are less represented and can be considered as emerging areas with high potential for technological innovation (fig. 5). The disparity in technological developments related to *P. crassipes* can be explained by varying regional priorities, resource availability, and market demands. For instance, bioremediation and bioenergy technologies are more prevalent due to their immediate environmental and economic benefits, particularly in regions with severe water pollution or energy deficits (Bakrim *et al.*, 2022). In contrast, areas such as pharmaceuticals and biomaterials are less developed, likely due to the higher complexity and costs associated with research and commercialization. To increase the development of underrepresented technologies, targeted funding for interdisciplinary research, public-private partnerships, and incentives for pilot projects could be implemented. Fostering international collaboration and knowledge sharing could accelerate innovation in these areas (Karouach *et al.*, 2022).

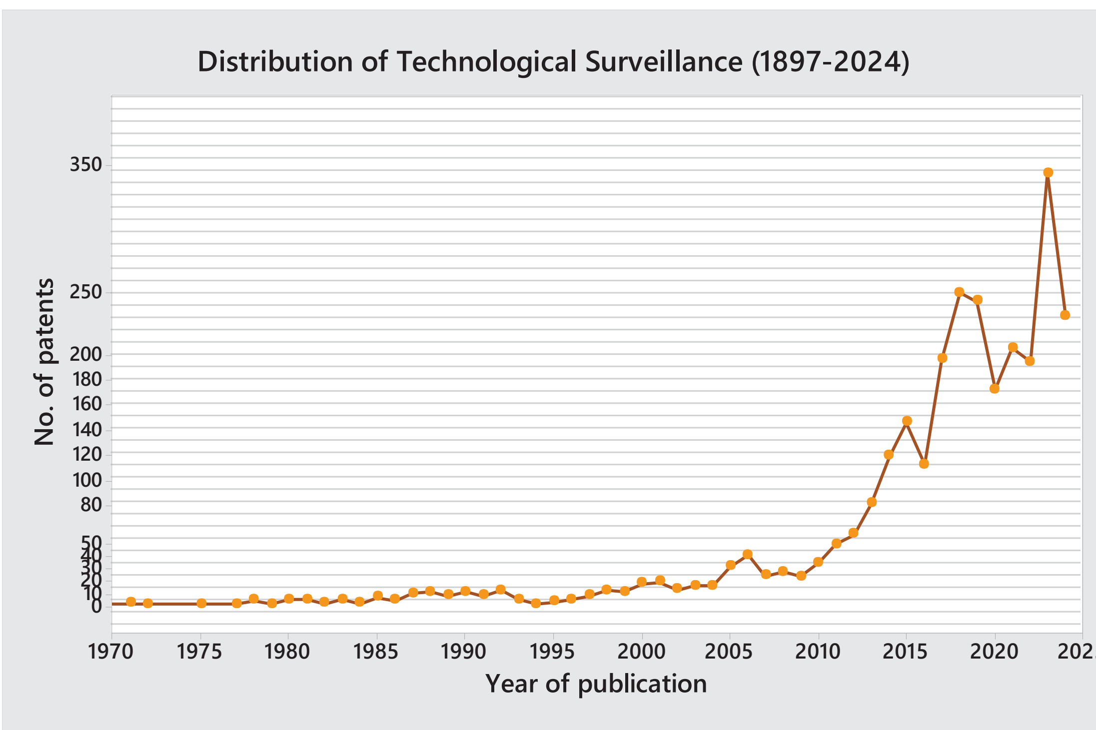


Fig. 2. Historical trend in patent registration for *Pontederia crassipes* over the past 50 years. This figure illustrates the temporal evolution of patent applications and issuances related to the species as of November 2024.

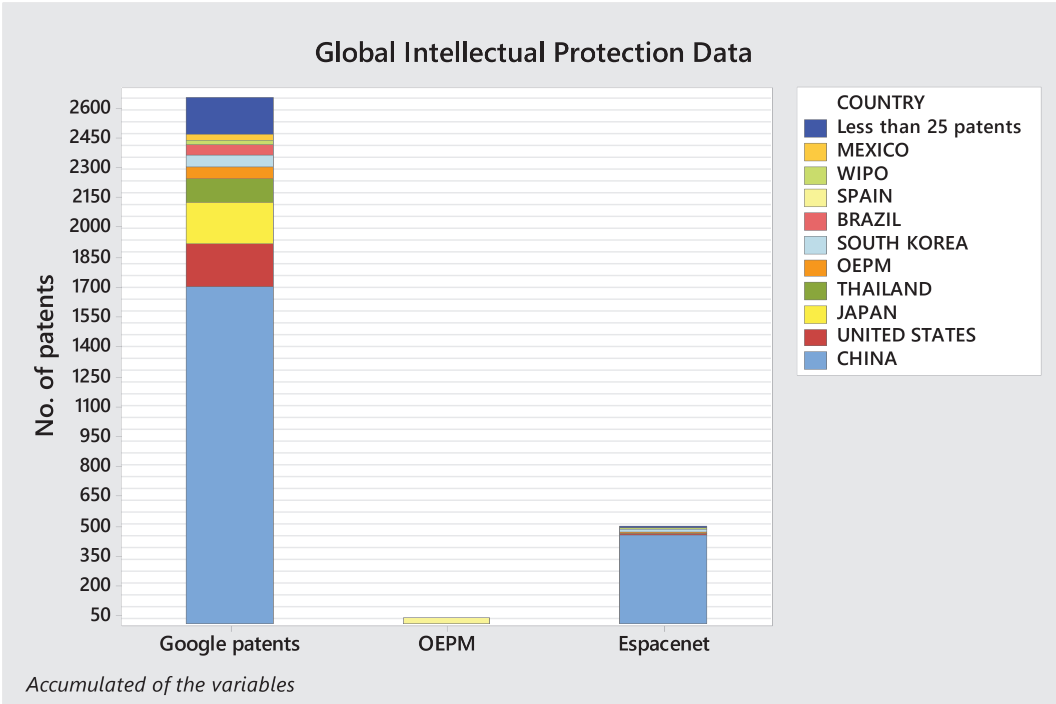


Fig. 3. Patents registered globally related to *Pontederia crassipes.* A comparison of patents associated with the species registered in various regions, based on data from Google Patents, Espacenet, and OEPM.

Additionally, managing and controlling water hyacinth faces significant financial and logistical challenges. A major barrier is the lack of precise national cost estimates for controlling its spread and the direct and indirect economic losses it produces (Niño-Sulkowska & Lot, 1983; Rodríguez-Lara *et al.*, 2022; SIL, 2017). The present analysis highlights the need for integrated control strategies to mitigate the economic, social, and ecological impacts.

Regarding the data obtained in the present research, utilizing water hyacinth biomass has become a key alternative for mitigating its environmental impact and limiting its spread in Mexico. Recent studies agree that the chemical characterization of its compounds reveals high potential for use in various industries, including chemical, pharmaceutical, and construction sectors (Martínez-Jiménez & Gómez-Balandra, 2022; Espinosa-García & Villaseñor, 2017; SIL, 2017).

## DISCUSSION

The water hyacinth, recognized for its invasive capacity, stands out as a highly adaptable species with efficient propagation mechanisms (Rodríguez-Lara *et al.*, 2022; Oduor *et al.*, 2023). The ability of *P. crassipes* to colonize water bodies is largely due to its efficient dispersal and reproductive mechanisms. The species propagates both sexually through seeds that can remain viable for up to 20 years, and asexuall, through stolons and fragments (Barrett & Forno, 1982; Ghoussein *et al.*, 2023). Additionally, its dispersal is facilitated by natural factors, such as water currents, and human activities, such as transport via boats (MITECO, 2019; Rodríguez-Lara *et al.*, 2022). These characteristics, along with its morphological and phenological adaptability, explain why *P. crassipes* is so difficult to control, and why its biomass represents an opportunity for innovative applications in areas such as bioremediation, bioenergy, and biomaterial production. The plant's morphological and reproductive characteristics, such as its size, bulbous petioles, and fasciculate roots, are crucial for its colonization ability, enabling survival under varying environmental conditions reinforcing its invasive potential (Ghoussein *et al.*, 2023).

*Pontederia crassipes* benefits from dual reproductive strategies (sexual and asexual), along with long-lasting seed viability (up to 20 years) and effective dispersal via water currents and human intervention, all of which amplify its invasiveness (Barrett & Forno, 1982; Ghoussein *et al.*, 2023). These traits enable quick colonization and ecosystem disruption, necessitating integrated management strategies such as seed bank control, mechanical removal, and biomass utilization to mitigate its spread (Coetzee & Hill, 2012; Karouach *et al.*, 2022). Its persistent seed bank and vegetative spread hinder eradication in the environment (Barret & Forno, 1982; Godana *et al.*, 2022). Additionally, flowering during specific periods facilitates massive propagule dispersal, significantly impacting invaded ecosystems (Rodríguez-Lara *et al.*, 2022; Ghoussein *et al.*, 2023).

Water hyacinth's dispersal mechanisms stand out for their efficiency and versatility. For example, hydrochory allows downstream expansion, while anthropogenic activities like navigation and equipment transportation aid its establishment in new habitats (MITECO, 2019; Rodríguez-Lara *et al.*, 2022). This dual dispersal approach underscores the urgency of implementing comprehensive and preventive management measures. Although few information is well documented regarding the pollination process, its flowers attract pollinators, suggesting a complementary role in its perpetuation (Ghoussein *et al.*, 2023). The combination of these mechanisms positions the water hyacinth as a significant threat to biodiversity and aquatic ecosystem functionality. While China and the U.S. lead in *P. crassipes* innovations, their success requires evaluation. Key aspects include scalability, cost-benefit, and environmental impacts. For Mexico, adapting these technologies demands tailored strategies due to infrastructure gaps. Future research should assess these factors to ensure sustainable and effective implementation (Liu *et al.*, 2016; Carreño-Sayago & Rodríguez-Parra, 2018).

Regardless of the data reported, water hyacinth biomass offers a dual solution: controlling the plant's proliferation while utilizing its components for industrial and environmental applications. The high biomass production and nutrient absorption capacity of *P. crassipes* make it suitable for bioenergy, bioremediation, and biomaterial production (Carreño-Sayago & Rodríguez-Parra, 2018; Bakrim *et al.*, 2022). Timing harvests before flowering can reduce seed production while maximizing biomass yield, offering a dual benefit of control and resource utilization (Rodríguez-Lara *et al.*, 2022). Integrating these strategies can offset management costs and create economic opportunities (Espinosa-García & Villaseñor, 2017). Recent studies highlight its potential for producing bioplastics, biofuels, and biopolymers (PHB) (Radhika & Murugesan, 2012; Bakrim *et al.*, 2022). These applications not only mitigate the plant's ecological impact but also create viable economic opportunities.

Additionally, extracts from *P. crassipes* have demonstrated promising antimicrobial and antifungal properties, paving the way for developments in the biomedical industry (Shanab *et al.*, 2010; Sitoe & Van Wyk, 2024). This versatility makes water hyacinth a valuable resource for sectors such as pharmaceuticals and bioremediation, a subject not well studied, but which can be considered a powerful tool.

Despite its potential, managing water hyacinth continues to face logistical and financial barriers. Particularly, in Mexico, estimates of control costs and associated economic losses are currently lacking our knowledge (Niño-Sulkowska & Lot, 1983; SIL, 2017). Technological monitoring efforts, particularly in China and the U.S., have advanced bioremediation, agro-inputs, and biofuel innovations (Espinosa-García & Villaseñor, 2017; Pinho & Mateus, 2023). This approach highlights the importance of international collaboration and investment in sustainable technologies to overcome these challenges and provide more suitable solutions.

In Mexico, the concentration of patents related to *P. crassipes* in regions such as Mexico City and Jalisco reflects a growing interest in the biomass's value as a raw material for chemical and pharmaceutical products (Martínez-Jiménez & Gómez-Balandra, 2007; Espinosa-García & Villaseñor, 2017). These patterns emphasize the importance of continuous monitoring to understand the dynamics of technological evolution and its implications across various sectors. However, this model

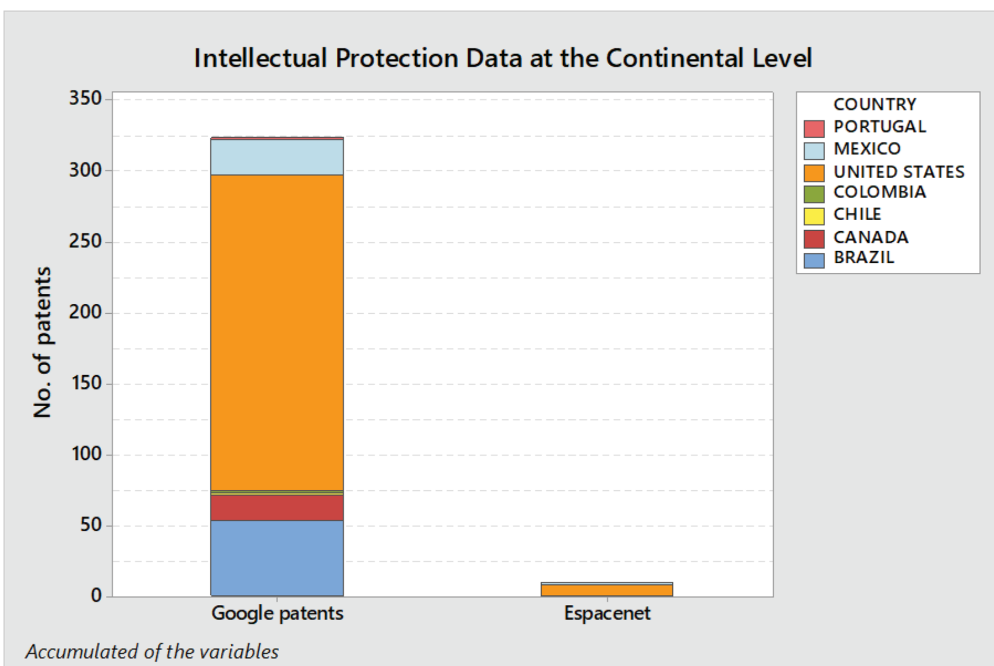


Fig. 4. Distribution of intellectual property protection for *Pontederia crassipes* across major continents. This figure presents data on patents related to the species, broken down by continent, highlighting regions with the most activity in this field. Data sourced from Google Patents and Espacenet.

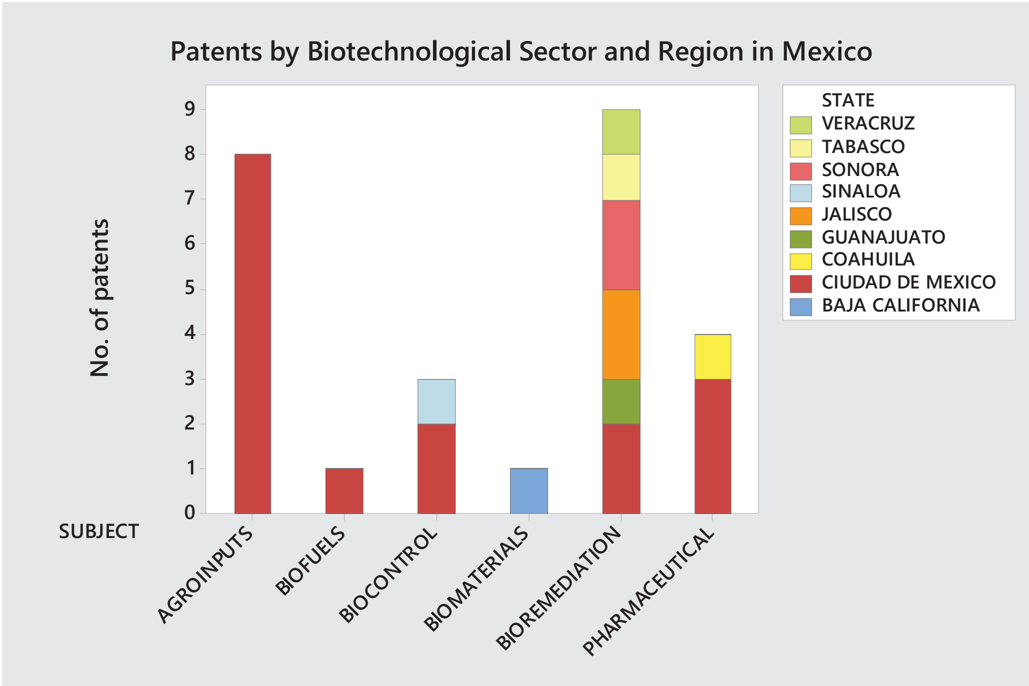


Fig. 5. Analysis of products developed under intellectual property protection in Mexico related to *Pontederia crassipes*. This figure outlines the main topics addressed in patents and the status of their issuance, based on data from Google Patents and Espacenet.

could be replicated in other regions, fostering a circular economy based on sustainability. The findings highlight the potential of *P. crassipes* as a promising resource while addressing its management to mitigate its adverse effects on aquatic systems. For example, considering Google Patents, which accounts for the vast majority of registered patents, a great disparity underscores the need for enhanced innovation policies and international collaboration in countries with lower patent shares to bridge the gap and foster a more balanced intellectual property landscape across the continent. In general, the dominance in the findings underscores the country's commitment to leverage water hyacinth in various applications, likely driven by both environmental management and economic opportunities. Despite the current barriers in its management, technological innovation and the sustainable use of its biomass, as discussed in this review; represent a solution that promises to impulse global interest issues, such as circular economy and conservation of ecosystems. Future research should focus on cost-effective harvesting, scalable bioremediation, and efficient biomass conversion. Interdisciplinary approaches and collaboration between governments, academia, and the private sector are essential to developing sustainable solutions for managing *P. crassipes* (Karouach *et al.*, 2022; Rodríguez-Lara *et al.*, 2022).

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