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Title

Biological control and biomass valorization of an invasive aquatic plant: Insights and practices from stakeholders managing the species in Portugal

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Abstract

Water hyacinth (*Pontederia crassipes*) is one of the most problematic aquatic invasive species in the world, including in Portugal. It causes significant ecological and economic impacts requiring measures to manage it and mitigate damage to water bodies. The BioComp_3.0 project aims to enhance the effective management of the species by aligning with circular economy principles and promoting sustainable solutions. It focuses on mitigating the impacts of massive biomass accumulation through composting, making it suitable for use in farming. This study analyses the perceptions and management practices of entities responsible for controlling water hyacinth, with a focus on monitoring, biological control, and biomass valorisation. Through a survey targeting management entities, we identified key challenges, including gaps in data collection, a limited understanding of biological control, and concerns about the risks associated with composting water hyacinth biomass. Over 60% of respondents confirmed the presence of the species in their intervention areas, yet many were unable to quantify its spread. Most entities rely on mechanical and manual removal methods, while lacking awareness and revealing uncertainty about effectiveness of biological control. Biomass composting is seen as a potential solution but concerns about species dispersal and economic dependency exist. Despite these challenges, 42.3% of entities are interested in joining a collaborative management network, suggesting opportunities for the crucial coordinated actions that is needed. The study highlights the need for integrated management strategies, including improved monitoring technologies, awareness campaigns on biological control, and strict protocols for biomass valorisation in order to promote responsible and scientifically informed management practices.

Keywords:

Biomass composting, Management of invasive plants, Sustainability, Valorisation of invasive species, Water hyacinth (*Pontederia crassipes*)

Author Contributions:

HM: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing.

EM: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing.

ASN: Methodology, Investigation, Formal Analysis, Data Curation, Visualization, Writing- Original Draft, Writing- Reviewing and Editing.

Competing Interest Statement:

The authors declare that they have no competing interests.

1) Introduction

Invasive alien species (IAS) are a subset of alien species that succeed to establish and spread, causing negative impacts on the environment, economy and, in some cases, on human health and good quality of life. In 2019, IAS contributed, either alone or in combination with other factors, to 60% of recorded global extinctions, with the annual global costs of biological invasions estimated at over 423 billion US dollars, varying across regions (IPBES 2023). Water hyacinth (*Pontederia crassipes* (Mart.) Solms.) is one of the species that significantly contributes to these estimated costs and global impacts on biodiversity (Abba and Sankarannair 2024; Cuthbert et al. 2021), making it urgent to intervene to minimise its impacts. The species is native to Brazil and other South American countries and has invaded lakes and wetlands in over 50 countries, as a result of anthropogenic dissemination (Coetzee et al. 2017; Villamagna and Murphy 2010). It is one of the most widespread invasive aquatic plants in the world (Datta et al. 2021), showing extremely rapid growth rate and prolific reproductive capacity (Malik 2007). Under favourable growth conditions, water hyacinth can double its biomass in 6–18 days (Keller and Lodge 2009), and in just eight months, a population starting with 10 plants can expand to 655,360, covering ca. half a hectare (Gunnarsson and Petersen 2007). The widespread presence of water hyacinth in aquatic ecosystems causes severe consequences, disrupting water use for irrigation, livestock farming, navigation, and recreational activities. Additionally, the blockage of canals and rivers can lead to flooding (Singh and Kalamdhad 2015) and large masses of decomposing material can degrade the quality of water resources and threaten the survival of native species (Oliveira et al. 2023).

Water hyacinth has been highly problematic in Portugal since it was first documented in the Sado River basin in 1939 (Guerreiro 1976). Recognized as a harmful species for over 50 years, its commercialisation has been prohibited since 1974 (Decree-Law No. 164/74). Today, it is included in the National List of Invasive Species (Decree-Law No. 92/2019) and, due to its high (risk of) invasiveness in the European Union, is also listed as an IAS of Union Concern (Regulation (EU) No. 1143/2014). The mechanical control of this plant generates very high economic costs in the Iberian Peninsula. The removal of 200,000 tonnes over 75 km in the Guadiana River basin, near the border between Portugal and Spain, amounted to €14.68 million between 2005 and 2008 (Dagno et al. 2007; EEA 2012). According to The Confederación Hidrográfica Del Guadiana (2021), €50 million have been spent in Spain since 2016 on direct expenses for its control; additional estimated €27.78 million are predicted to be spent on the strategy to combat water hyacinth between 2021-2027. In Portugal, EDIA, the company managing the Alqueva and related dams - the largest strategic water reserve in Europe - spent approximately €1.5 million on water hyacinth management between 2012 and 2023 (Personal communication EDIA 2024). Although very costly, the strategies to manage this species have not been very effective. Although it is a legally prohibited species, farmers have been observed using water hyacinth to enrich the soil and feeding it to cows and sheep (Personal observations Palhas 2025). The search for more sustainable solutions encouraged research into possible uses of water hyacinth, including those integrated with control methods, that may contribute to increase management success.

Composting allows wastes to be valorised, reducing their size and volume and obtaining a valuable final material (compost) that can be used as fertilizer or soil amendment (Cadena et al. 2009). This practice transforms biological wastes into a valuable product, replacing non-renewable resources with biological alternatives, aligning with the principles of the Circular Bioeconomy (Cortés et al. 2020; D'Adamo et al. 2021). Composting occurs through the biological degradation of organic matter by aerobic microorganisms. While biodegradation naturally takes place in the soil, composting intensifies the process under controlled conditions, resulting is a nutrient-rich compost that can be used as fertiliser (Bong et al. 2017; Hermann et al. 2011).

The conversion of water hyacinth biomass waste into organic compost for agriculture has emerged as a potential solution to manage the large volumes of biomass produced by mechanical control Some studies suggest that water hyacinth compost may be effective in promoting the growth of agricultural plants. For example, Osoro et al. (2014) successfully produced organic compounds from water hyacinth leading to increased corn production. Similarly, Mazumder et al. (2019) analysed water hyacinth removed from a contaminated lake and concluded that the resulting compost was suitable for use as fertiliser. Greenhouse trials showed that lettuce plant biomass production was higher in pots fertilised with water hyacinth and sawdust compost, being similar to commercial organic fertilisers, and superior to compost made from water hyacinth and wood chips (Oliveira et al. 2024).

Valorisation is only one aspect of the economic evaluation of an IAS. According to Emerton and Howard (2008), when an IAS is undervalued, a primary concern in economic analysis is assessing the incremental changes that occur when the species occupies a space, thereby interfering with the functioning of an ecosystem (whether natural or human-modified) that generates economically valuable goods and services. In doing so, the IAS displaces other species (original or native) or alters biological associations, leading to losses in biodiversity and ecosystem functions. The BioComp_3.0 project (2021-2025) is testing the production of organic biological composts from water hyacinth, allowing for its valorisation alongside agro-pastoral, forestry, and agro-industrial by-products. The project focuses on responsible and informed valorisation, with the involvement of stakeholders (BioComp_2.0 2021). Sustainable solutions for IAS must also include control, and classical biological control (CBC) may be one of the most sustainable alternatives. CBC involves the use of a natural enemy, such as a parasite, predator, or pathogen, from the native range of the IAS to keep its population density at lower levels than would occur in its absence (DeBach and Rosen 1973). In Mexico, since 1970s, the weevils *Neochetina eichhorniae* (Warner) and *Neochetina bruchi* (Hustache) have been used successfully to feed on the leaves and petioles of water hyacinth (Jiménez and Balandra 2007) and in Florida, since 2010 and South Africa, *Megamelus scutellaris* (Berg) (Hemiptera: Delphacidae) feeds on the plant's phloem (Goode et al. 2021;Miller et al. 2023). Despite being carried out with increasing safety and rigour, CBC remains controversial, as it involves the introduction of a new species into the environment. Therefore, properly informing and engaging citizens and stakeholders is crucial. However, research on public perceptions of CBC remains scarce and fragmented, especially among the scientific and technical communities (Marchante et al. 2023a). Efforts to prevent and mitigate the impacts of IAS require the involvement of the whole society. Investments in public awareness, including engagement and communication with the public, not only enhance awareness (Marchante and Marchante 2016; Verbrugge et al. 2021) but also improve public support for the needed management (Cordeiro et al. 2020). This is essential because the management of natural resources involves more than science, and its success depends on public acceptance, knowledge transfer, resource availability, and competing objectives (Moffat et al. 2024).

The present study, conducted within the scope of the project BioComp_3.0, aimed to analyse perceptions and knowledge about water hyacinth in Portugal among different management entities, through a survey. It sought to explore opinions on the water hyacinth invasion problem, its valorisation through organic composting, and biological control.

2) Material and Methods

The text of this article has been translated with the help of ChatGPT (artificial intelligence) and has been reviewed to ensure accuracy.

Survey and target public

This study was conducted in Portugal, covering both the mainland and islands. It targeted entities involved in managing, or potentially managing, areas affected by water hyacinth, including activities such as prevention, surveillance, containment and control. These entities included academy, nongovernmental organizations, municipalities, private companies, etc. To identify and reach the target entities, an internet search was conducted to gather contact details of entities located in areas surrounding water bodies invaded by water hyacinth. Data on water hyacinth locations were obtained from **GBIF** (GBIF.org 2024) for the period between 2007 and 2024. In addition, further contacts were gathered from the Portuguese Network for the Study and Management of Invasive Species (InvEco) (Marchante et al. 2024) and during IAS awareness and training sessions held across the country, by the authors.

Questionnaire design and data collection

The survey was conducted using a questionnaire (Suppl. material 1) created with Google Forms, in Portuguese, and made available online. A test version was first presented to a limited number (10) of respondents to evaluate clarity of the questions; after their responses, only minor adjustments were made in six questions and the final version prepared. It was then disseminated via mailing list to a total of 570 email contacts on May 17, 2024: 211 gathered through online searches, 17 provided by members of the BioComp_3.0 project, and 342 from the InvEco network. A follow-up message was sent on July 3, and a final one on July 18 to the contacts who had not yet responded. The survey was open to receive answers until July 31, 2024. The questionnaire consisted of 31 questions, some with follow-up questions; most of the questions were close-ended, with only a few open-ended (Table 1). It was divided into five sections: Section I aimed to gather information about the respondent, its geographical area of intervention and presence/absence of water hyacinth in it. Section II asked about the situation of water hyacinth invasion in the geographical area of the respondent. Section III was focused on understanding how the entities manage water hyacinth and which funding sources they have used. The following Section IV, aimed to understand the opinion and knowledge of the respondents regarding the use of biological control to manage invasive alien plants in Portugal, including water hyacinth. Finally, Section V focused on the valorisation of IAS, including the organic composting of water hyacinth (Table 1).

Table 1- Summary of the questionnaire sent to entities involved in managing water hyacinth (*Pontederia crassipes*) in Portugal, including the type of questions.

Section	Aim	Question	Type of question	
I	Characterization of the organization	Q1, Q2, Q3, Q3.1, Q5	Open-ended	Short answer
		Q4	Close-ended	Multiple choice
				Single response
II	Invasive situation's characterization	Q6, Q7, Q9, Q10	Close-ended	Multiple choice
				Single response
		Q8	Close-ended	Multiple choice
				Multiple choice
III	Water hyacinth management	Q11, Q14, Q16	Close-ended	Multiple choice
				Single response
		Q12, Q13, Q15, Q17	Close-ended	Multiple choice
				Multiple response
		Q18	Open-ended	Long answer
IV	Knowledge biological control	Q19, Q20, Q22	Close-ended	Multiple choice
				Single response
		Q21, Q23	Open-ended	Long answer
		Q24	Close - ended	Multiple choice
				Multiple response
V	Opinion about organic compounds obtained from water hyacinth	Q25, Q26, Q27, Q28, Q29	Close-ended	Multiple choice
				Single response
		Q30	Close-ended	Multiple choice
				Multiple response
		Q31	Open-ended	Long answer

Data analysis

The answers to the questionnaire were first analysed using simple descriptive statistics. Maps were done at **QGIS** (QGIS Development Team 2020) to represent answers to questions Question 2, Question 4, and Question 5. Sankey diagrams (Displayr 2025) were used to better visualize the relationships between Question 25, Question 26, Question 27, and Question 28.

All graphics (except Sankey diagrams) and descriptive statistics were performed on R version 4.2.3 (R Development Core Team 2022).

3) Results

Of the 570 emails sent, 106 responses were received, corresponding to ca. 18.6% response rate. Of these, 97 were considered valid (17%), with six being eliminated because they were duplicates, and three because the respondents didn't agree with the collection of data.

Respondents' characterization (Section I)

Most responses were obtained from entities located in the central, more littoral region of Portugal, with geographical areas of intervention varying in size (Figure 1). Among the responses, 35.1% came from municipal entities, 27.8% from associations (cultural, sports, social, agricultural producers, NGOs, forest producers), 13.4% from public institutes, 8.2% from private companies, 7.2% from Intermunicipal Communities (CIM), 7.2% from state internal administration bodies, and 1% from an independent entity. Of the respondents, 60.8% indicated that water hyacinth was present in their intervention area, while 23.7% did not acknowledge its presence, and

15.5% responded that the species might be present but could not confirm it.

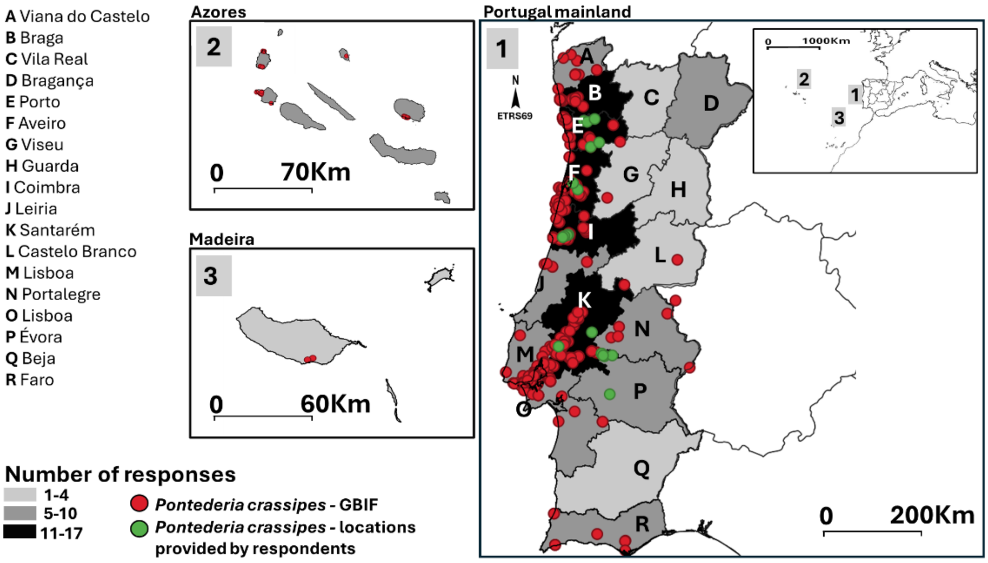

Figure 1- Geographical areas of intervention of the entities that responded to the survey. The colour scale (greys and black) represents the number of responses per district on the mainland, as well as the Azores and Madeira archipelagos.

Characterization of the invasion by water hyacinth (Section II)

Most respondents (60.8%) recognised the invasiveness of water hyacinth in their area of intervention. Of those, nearly a third (32.3%) acknowledged the presence of the species but were unable to quantify the area occupied; about a quarter (24.6%) stated that water hyacinth covers areas larger than 20 ha, while 15.4% indicated much smaller areas, less than 1 ha, with others reporting intermediate areas. Additionally, 4.6% referred that the area invaded varies due to management efforts (Question 7; Figure 2a). Several damages of water hyacinth directly affecting the entities were identified, with the most significant being losses on aquatic sports (15.2%), fishing (15.9%), and leisure (17.2%) activities. Meanwhile, 14.6% stated that their entity was not directly affected by water hyacinth (Q8; Figure 2b).

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The date of introduction of water hyacinth was quite variable. According to one-quarter of the respondents, water hyacinth was introduced in their intervention region around 2010, but ca. 10% stated it arrived before the 1970s and 15% assumed its introduction only very recently (2020). Nearly one-fifth were unable to specify when the species arrived in their areas (Q9, Figure 2c).

Regarding the pathway of arrival, over half of the respondents (52.5%) were not aware of how the species was introduced into their areas; a third answered it was introduced due to ornamental use, either accidentally (e.g., escaping from garden ponds or tanks, 23.7%), or intentionally (11.9%). A minority (8.5%) provided other explanations, such as the natural progression from upstream either in the Guadiana River (from the Spanish side of the border, in the South) after major floods of 2001, or from Pateira de Fermentelos (in Águeda/Aveiro) when water hyacinth occupied a large area (Q10, Figure 2d).

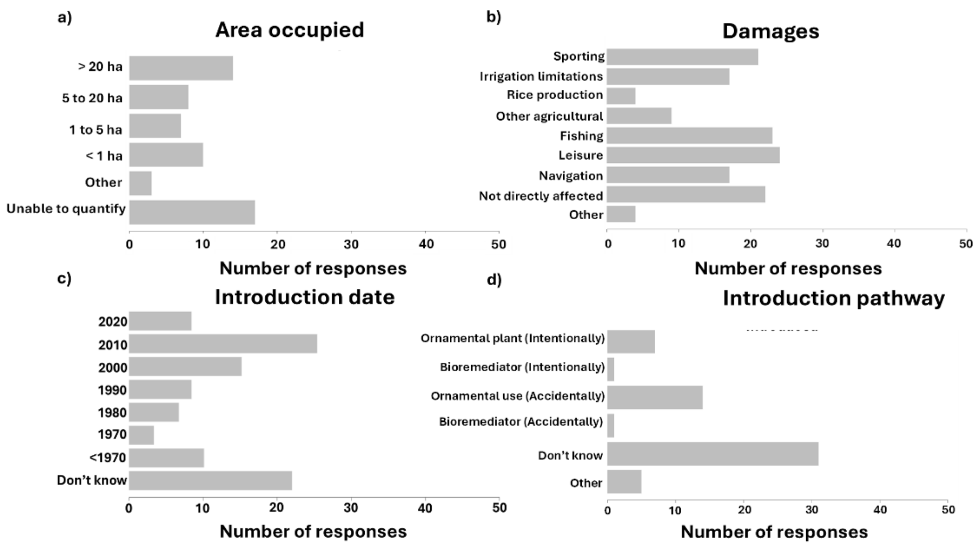

Figure 2- Local perceptions and impacts related to the presence of water hyacinth (*Pontederia crassipes*), as reported by survey respondents: **a)** Proportion of the area occupied by water hyacinth (Q7, n=59), **b)** Damages caused by water hyacinth (Q8, n=141), **c)** Approximate date of the species' arrival (Q9, n=59), and **d)** Reported introduction pathways (Q10, n=59).

Management of water hyacinth (Section III)

Regarding management actions focused on water hyacinth, 62.7% of entities reported that they carry/ have carried out control actions, while 27.1% have never done so. The remaining respondents either did not know (5.1%) or provided other responses (5.1%), such as reporting the issue to relevant authorities or carrying out awareness-raising actions. Nearly a quarter of respondents reported carrying out containment measures, namely to prevent the invasion from neighbouring areas. One-fifth (19.1%) undertook preventive actions, such as awareness-raising initiatives on invasive species, and another fifth (21.4%) were engaged in ongoing control efforts. Despite being performed by fewer entities, it is worth mentioning that 15.5% have been conducting surveillance for the early detection of the species (Q12, Figure 3a).

Manual control was used by one-quarter (24.1%) of the entities, while ca. one-third employed mechanical control, using equipment/machinery (excavators and bulldozers) from the shore (20.3%) or within the water body, such as aquatic or amphibious harvesters (16.5%). Additionally, 17.7% contained the spread of the species by applying floating barriers, and only 2.5% used chemical control (Q13, Figure 3b).

Financial resources spent by entities over the past five years for the management of water hyacinth were variable and ranged from less than €1,000 (15%) to values between €20,001 and €100,000 (27.5%) or higher than that (7.5%). 20% respondents were unable to quantify the costs, despite acknowledging them (Q14, Figure 3c).

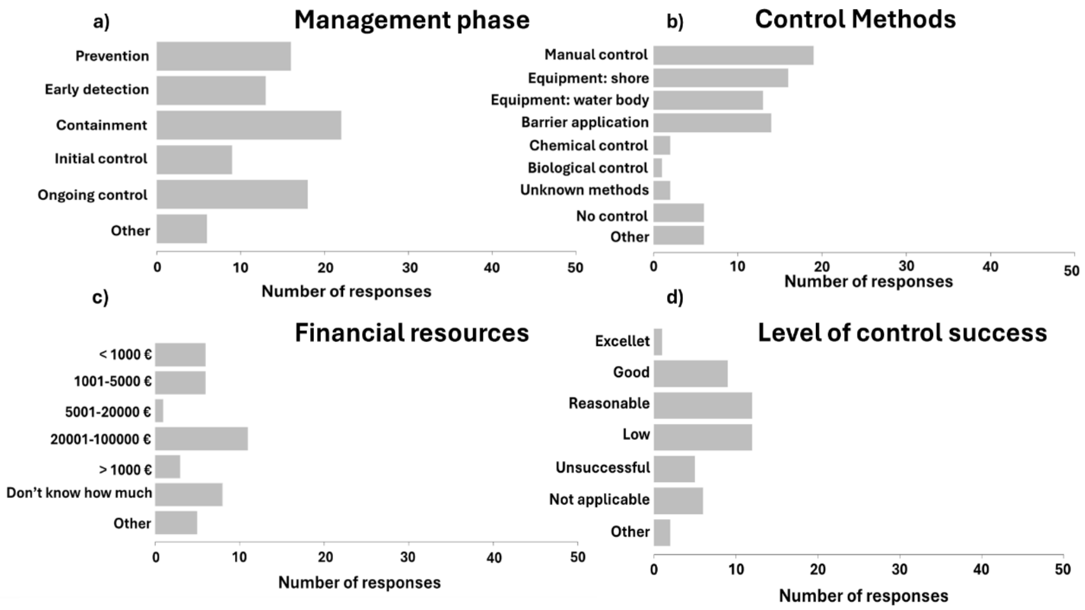

Figure 3- Aspects of management of water hyacinth (*Pontederia crassipes*) as perceived by respondents, regarding: **a)** Management phases undertaken by respondents' entities (Q12, n =84), **b)** Methods that are or have been used by entities to control the species (Q13, n=79), **c)** Financial resources (approximate total value) used by the entities, over the past five years for the management of water hyacinth (Q14, n=40), **d)** Level of success of the interventions carried out by the entities (Q17, n=47).

For 43.4% of the respondents, funding for the management of water hyacinth comes from the entity's own resources, while 24.5% mentioned resorting to national funds from the National authority for conservation (Environmental Fund). Of the other funding sources mentioned, the most frequently used was POSEUR (9.4%).

Regarding the frequency of control measures, 28.9% of respondents stated that control was carried out continuously, 18.4% annually, 13.2% monthly, and 2.6% quarterly. Finally, 13.2% know that control was carried out but were unsure of its regularity and 23.7% provided other options (sporadic control, biweekly, occasionally, just starting, no established regularity).

The success of management actions was quite variable. Only 2.1% of the respondents indicated that their entity had an excellent level of success, corresponding to eradication of water hyacinth in their areas, with no plants or propagules remaining. Almost three-quarters of the responses were quite evenly distributed in three categories: 19.1% had good success, as they were able to control the water hyacinth - the species still exists but at reduced densities, without impacting human activities or the conservation of local fauna and flora; 25.5% achieved moderate success - the species still exists, allowing most human activities, but the density increases regularly, requiring new control measures; 25.5% indicated reduced success, despite the measures implemented. 10.6% entities assumed that control interventions were unsuccessful, as the current situation was worse than before the interventions and another 10.6% only focused on prevention and monitoring. Finally, 4.3% didn’t have information to answer properly (Q17, Figure 3d).

Classical Biological Control (CBC) (Section IV)

A significant number of respondents considered CBC a risky (26.8%) or very risky (3.9%) alternative for managing invasive plants, fearing that the agents used might affect non-target species. However, 21.6% viewed CBC as a safe and more sustainable method, 8.2% considered it a cost-effective alternative that should be used more often in conjunction with other methods, and 9.3% said CBC was the best option for controlling invasive plants. Nearly one-third (30.9%) stated that they were not sufficiently informed about CBC to answer.

When it comes to the knowledge about the use of CBC specifically in Portugal to manage invasive plant species, 10.3% of respondents were not aware of its use, 50.5% confirmed that they were aware of it, while 39.2% indicated they did not know. Within respondents aware of CBC in Portugal, 44.9% properly acknowledged its use against *Acacia longifolia*, 40.8% generalized it for *Acacia* species, and occasionally it was referred its used for other species (Q20, Q21).

After being informed that in other regions of the world specific biological control agents are used to manage water hyacinth, respondents were asked whether, providing that all necessary tests and risk analyses were conducted, they would agree with its use to control water hyacinth in Portugal. A total of 63.9% said they would agree, only 4.1% responded that they would not agree, 29.9% had no opinion, and 2.1% chosen other options.

According to respondents' knowledge about the specific biological control agents for water hyacinth, 40.1% of were familiar with the stem-feeding weevils (*Neochetina bruchi* and *N. eichhorniae*) being the most mentioned (15.2%); 59.9% have never heard of any agent (Suppl. material 2)

Valorisation: Organic compounds obtained from water hyacinth (Section V)

To better understand the respondents' answers, the results were correlated as shown below (Figure 4). Most respondents agreed with the valorisation of invasive species (74.2%) (Figure 4, left). Amongst them, the majority considered that it should only occur if the goal was the total elimination of the species (66%), while a smaller group considered that valorisation was always beneficial due to the economic return (8.2%). Those who disagreed with valorisation highlighted the risks of spreading the species (11.3%) or give rise to dependency on the resources created (9.3%).

When focusing the production of compost from water hyacinth (Q26 and Q27), the majority of those who supported the total elimination of the species completely agreed with this use. On the other hand, those who fear the spread or dependency on the species tended to disagree, either totally or partially (Figure 4). In the question concerning the possibility of producing compost responsibly without creating dependency, those who initially supported valorisation with the aim of species elimination remained largely in favour, while those who expressed concerns tended to disagree, either totally or partially (Figure 4, right).

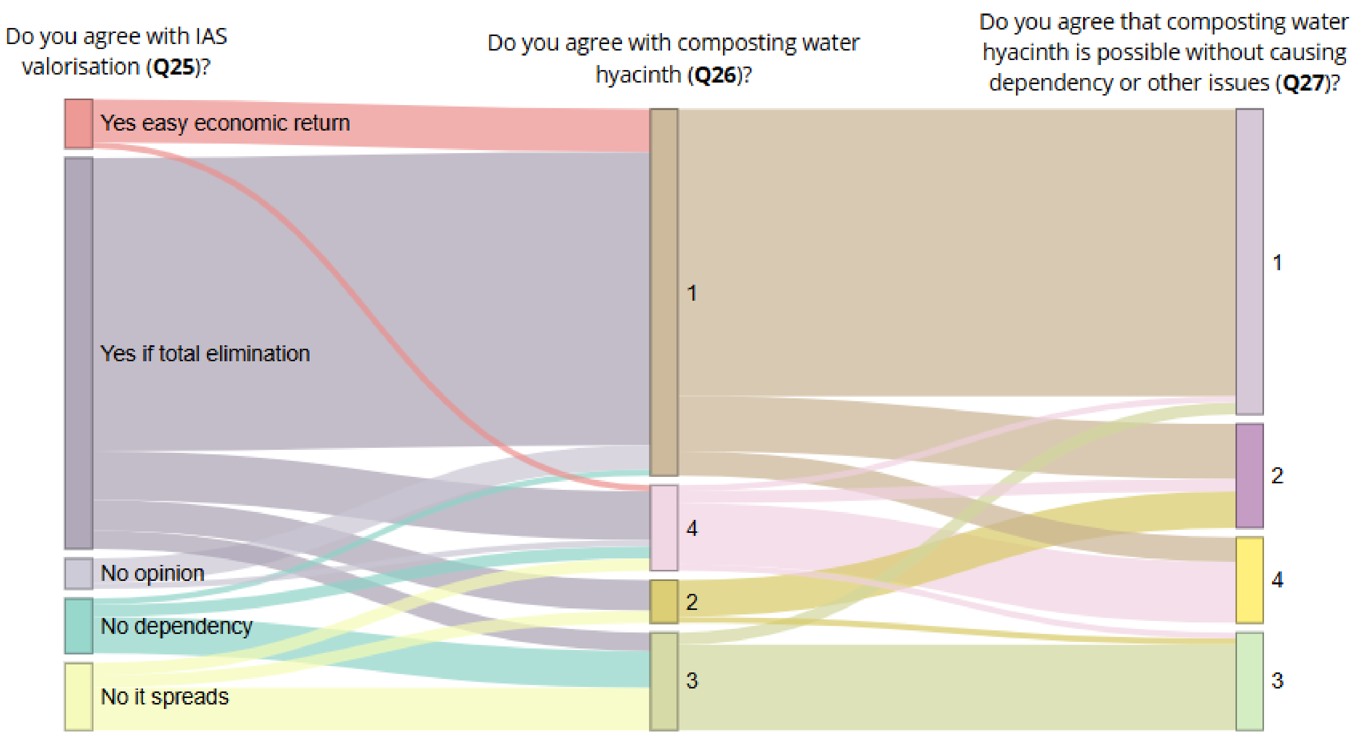

Figure 4 – Sankey diagram illustrating the relationships of responses regarding the valorisation of an invasive alien species (**Q25**, left of the diagram), followed by the acceptance of organic compost production from water hyacinth (*Pontederia crassipes*, **Q26**, centre), and finally the feasibility of producing this compost without creating dependency on water hyacinth (**Q27**, right) (n=97). For **Q26** and **Q27**, **1** corresponds to Completely agree, **2** Partially agree, **3** Completely disagree, and **4** Partially disagree. Complete text of the questions and options in Suppl. material 1.

Most respondents fully or partially agree with composting water hyacinth alongside agro-forestry and agro-industrial by-products (61.9% and 7.2%, respectively). However, about a third disagree with this valorisation, either completely (16.5%) or partially (14.4%). Regarding the production of water hyacinth compost without risking further species dispersal (e.g., during transport or when using the compost), over half agree, fully (42.3%) or partially (14.4%) while many disagree completely

(20.6%) or partially (22.6%, Figure 5).

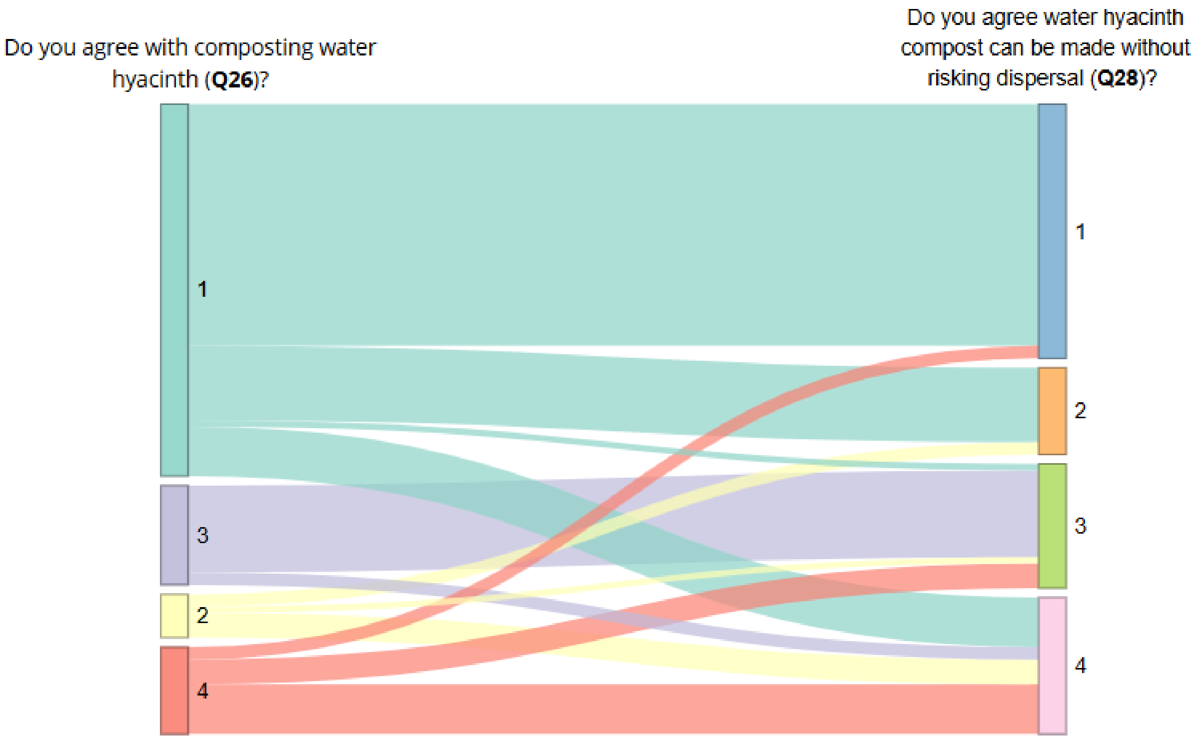

Figure 5 – Sankey diagram illustrating the relationship between the acceptance of organic compost production from water hyacinth (*Pontederia crassipes*), (**Q26**, left of the diagram) and the perception of the risk of species dispersion during this process (**Q28**, right, n=97). In both questions, **1** corresponds to Completely agree, **2** Partially agree, **3** Completely disagree, and **4** Partially disagree. Complete text of the questions and options in Suppl. material 1.

Respondents were asked about their interest in creating a network of responsible partners to cooperate in controlling most effectively water hyacinth. A large proportion either expressed interest in joining such a network (42.3%) or did not have an opinion but would like to be contacted in the future (43.3%), while a minority rejected the idea (14.4%).

Finally, respondents were asked to indicate two ways they considered most important for more effective management of invasive species, including water hyacinth; some respondents selected three options instead of two. A total of 42.1% of respondents stated the most important measure was the creation of dedicated, permanent, and well-trained teams for managing invasive species; 26.6% believed that the key priority should be greater investment in biological control, integrated with other control methods, to ensure a more sustainable approach to species management, and 27.8% indicated that securing more funding for managing invasive species was the most crucial factor. The remaining 2.9% suggested other options, e.g., ensuring the long-term continuity of control actions, reducing other pressures on ecosystems, and creating a collaborative network.

4) Discussion

The findings of this study highlight significant challenges and opportunities in the management and sustainable valorisation of water hyacinth in Portugal. While many managing entities recognise the presence of this invasive species in their intervention areas, the inability of almost a third to quantify the affected area, as well as other invasion-related parameters, points to a critical gap in both monitoring and record-keeping efforts by some entities. This lack of data from a significant part of the entities alerts to the absence of standardised methodologies for monitoring the extent of water hyacinth (and other invasive species) invasion, limiting the ability to assess its real impact (Kissling et al. 2024; Datta et al. 2021). Additionally, these eventual structural deficiencies in systematic surveillance, may hamper the development of effective and targeted early detection and control strategies (Garcia-Lozano et al. 2025). This is particularly relevant considering that the introduction of water hyacinth in new water bodies continues to occur (new records in 2020) as reported by some of the respondents. Given the acknowledged, although not quantified, ecological and economic impacts of water hyacinth invasion, addressing these weaknesses is essential for improving resource allocation and management efficiency. This challenge is not unique to Portugal, as other studies have shown that the effective management of invasive species is often hindered by a lack of robust and continuous monitoring systems (Felix et al. 2024). The reliance on occasional and inaccurate evidence rather than systematic data collection may exacerbates difficulties in controlling the spread of water hyacinth in some affected territories (Mouta et al. 2023). To overcome this issue, investment in advanced monitoring technologies, such as remote sensing, drone surveillance, and GIS-based mapping, could significantly enhance data accuracy and management planning (Pádua et al. 2022). Citizen science programs can also give a valid contribution (Marchante et al. 2023a).These tools have been successfully employed in other invasive species management programmes and have demonstrated their efficacy in providing real-time, high-resolution data on species distribution and density (Große-Stoltenberg et al. 2025; Haxaire et al. 2006). Additionally, training and capacity-building initiatives for local authorities and environmental managers could improve their ability to implement and interpret monitoring techniques effectively (Colaço et al. 2023).

The predominant management strategies for water hyacinth currently adopted by entities in Portugal rely on mechanical and manual removal methods, with biological and chemical controls being rarely mentioned. Though the reduced use of chemical control is definitely positive, being in line with the key commitment of the European Green Deal, and the One Health approach, biological control needs to be considered (Sun et al. 2022). While manual and mechanical control approaches are effective for short-term management, they are labour-intensive, costly, and often require continuous interventions to prevent reinfestation (Coetzee et al. 2017). Additionally, the outcomes are often insufficient, as recognized by the reduced or moderate success of many interventions reported by the entities, as happens with other invasive plants, namely Acacia species (Marchante et al. 2023b). Furthermore, these methods do not address the underlying factors facilitating the rapid growth and spread of water hyacinth, such as nutrient enrichment in water bodies (Abba and Sankarannair 2024).

Adoption of Classical Biological Control

The lack of use of biological control is particularly noteworthy. Despite its proven success in other regions, such as North and South America and parts of Africa, (Goode et al. 2021; Jiménez and Balandra 2007; Miller et al. 2023), classical biological control (CBC) remains underexplored in Portugal, as well as all-over Europe (Shaw et al. 2018) and as such is not used. This results in the lack of awareness and understanding of CBC methodologies among managing entities with a large group reporting insufficient knowledge on this topic. This can lead to misconceptions or uncertainties about CBC safety and effectiveness and may inhibit its implementation in the future (Marchante et al. 2023a).

The use of natural enemies from the native range of water hyacinth, such as weevils (*Neochetina bruchi* and *N. eichhorniae*) or the sap-sucking planthopper, *Megamelus scutellaris*, has been shown to not affect native flora (Goode et al. 2021). Research has demonstrated that these biological control agents can significantly reduce plant biomass over time (Goode et al. 2022), decreasing the need for costly mechanical interventions. However, effective implementation requires not only thorough risk assessment and regulatory approvals to ensure that non-target species and ecosystems remain unaffected but also support from land managers and other stakeholders to ensure that the biocontrol agents' populations, if/when released, are not eliminated by other methods (Malik 2007). Increased collaboration with researchers and institutions experienced in biological control could help bridge this knowledge gap and facilitate its future adoption as part of an integrated management strategy, as has happened with other species (López-Núñez et al. 2021).

Valorisation: organic compounds obtained from water hyacinth

The valorisation of water hyacinth biomass through compost production may represent a promising avenue to increase management sustainability (Beesigamukama et al. 2018). Organic composting offers a dual benefit: it provides an environmentally friendly disposal method for the large quantities of harvested biomass while also generating a valuable agricultural input to improve soil quality (Muoma 2016). Numerous studies have confirmed the effectiveness of compost derived from water hyacinth in improving soil fertility and crop yields (Mazumder et al. 2019; Osoro et al. 2014). In our study, many respondents expressed a positive stance towards the potential of biomass valorisation, albeit frequently with reservations regarding the risks of species dispersal and dependency risks. Concerns about unintentional propagation are valid, as improper handling of water hyacinth biomass could contribute to its spread rather than its control (Pérez et al. 2015). The risk of propagule survival during composting is a key consideration, and previous research has emphasised the importance of ensuring complete degradation of viable plant material through controlled composting conditions (Killick and Blanchon, 2018; Moffat et al. 2024). Therefore, any valorisation initiative must be accompanied by rigorous protocols to prevent accidental dispersal of the invasive plant. Selecting the most adequate season to collect the plants (avoiding to compost plants that bear flowers and/or fruits), high-temperature composting, extended decomposition periods, periodic testing for viable propagules, and implementation of good practices

(Pérez et al. 2015) and biosecurity procedures during collection and transport could mitigate these risks (Martins et al. 2021; Silva 2024).

Another frequently mentioned concern was the possibility of creating economic incentives that might become so attractive as to lead to the maintenance, rather than the elimination, of water hyacinth populations. This paradoxical effect may arise when invasive species become economically valuable resources disincentivizing control efforts and potentially resulting in the persistence of the invasive species (Barney 2014). To prevent such unintended consequences, clear regulatory frameworks should be established to ensure that biomass valorisation is solely aimed at the sustainable disposal of IAS, rather than promoting continued reliance on the invasive species (Van Meerbeek et al. 2015). Robust strategies to raise awareness and inform citizens are also crucial in this regard (Novoa et al. 2017).

Challenges & Opportunities

A particularly encouraging finding from this study was the willingness of 42.3% of managing entities to participate in a network of responsible partners for improved water hyacinth management. Collaborative approaches have proven successful in invasive species management by fostering information exchange, resource sharing, and coordinated action plans (Cordeiro et al. 2020; IPBES 2023; González et al. 2020; Marchante et al. 2024). However, a great proportion of respondents remained hesitant or uninterested in joining such initiatives, indicating potential barriers to engagement. Institutional limitations, financial constraints, and competing priorities may all contribute to this reluctance. Addressing these barriers requires targeted outreach and clear communication regarding the tangible benefits of collaboration (Tsiamis et al. 2016). Demonstrating successful case studies where network-based management has led to cost savings and increased efficiency could encourage greater participation (Abrahams et al. 2019). Additionally, securing external funding for joint initiatives could alleviate financial concerns and provide incentives for involvement.

The findings of this study highlight the pressing need for an integrated and multifaceted management approach to water hyacinth in Portugal. The current reliance on mechanical removal is neither economically sustainable nor environmentally sufficient to control large-scale invasions (Coetzee et al. 2017) Instead, a combination of improved monitoring, expanded research on biological control, safe and regulated biomass valorisation, and enhanced stakeholder collaboration is required to address this challenge effectively.

Investments in monitoring infrastructure and data collection mechanisms are essential and will provide a clearer picture of invasion dynamics and inform targeted management actions. The project BioComp_3.0 is developing tools than can contribute to this monitoring (BioComp_3.0 2025).

Increasing awareness and scientific outreach on biological control could help reduce scepticism (Marchante et al. 2023) and facilitate its integration into existing management frameworks. Additionally, developing and enforcing strict guidelines for biomass valorisation will ensure that composting initiatives contribute to eradication rather than perpetuation of the species (Nunes et al. 2021). Finally, fostering a culture of cooperation among managing entities through well-structured networks will enhance collective action and resource optimisation (IPBES 2023).

5) Conclusions

This study underscores the complexity of managing water hyacinth in Portugal and highlights the critical areas requiring attention for more effective control. While awareness of the species' impact is relatively high, gaps in monitoring and quantitative assessments by some entities, the lack of biological control, concerns regarding biomass valorisation and limited coordination amongst different entities remain key challenges. Nonetheless, the interest in collaborative management networks suggests a promising foundation for improving coordinated responses. By aligning management efforts with sustainable practices, such as responsible biomass utilisation, the BioComp_3.0 project can serve as a catalyst for the implementation of effective strategies. More broadly, ongoing research - including the consideration and testing of biological control - along with policy support and active stakeholder engagement, can help mitigate the ecological and economic threats posed by water hyacinth while transforming its biomass into a resource aligned with circular economy principles. Moving forward, a commitment to adaptive, evidence-based management will be essential to ensuring the long-term success of these interventions.

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