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REVIEW

Quantifying the effects of water hyacinth (*Pontederia crassipes*) on freshwater ecosystems: a meta-analysis

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Abstract Water hyacinth (*Pontederia crassipes*, used to be *Eichhornia crassipes*), one of the world's most notorious invasive species, poses significant threats to freshwater ecosystems worldwide. Despite its widespread presence in over 70 countries, there is a lack of comprehensive analyses about the impacts of water hyacinth. To fill this knowledge gap and to explore the multi-dimensional (physical, chemical, and biological) impacts of water hyacinth on freshwater ecosystems, we conducted a meta-analysis that synthesized data from 25 original studies encompassing 12 countries and three continents. We found that water hyacinth invasions lead to significant reductions in water dissolved oxygen levels (Standardized Mean Difference (SMD) = −2.26, 95% CI: [−3.94, −0.56]; $p = 0.001$) and nitrogen (SMD = −1.70, 95% CI: [−3.19, −0.20]; $p = 0.01$). We also observed non-significant but notable trends of decreased water pH levels and increased macroinvertebrates abundance, suggesting complex interactions between water hyacinth and abiotic factors. Our analysis underscores the need for more localized studies to better understand the general impacts of water hyacinth invasions. Given the significant ecological disruptions caused by water hyacinth, effective management strategies are imperative to mitigate the adverse effects of this invasive species. Overall, this meta-analysis provides valuable insights into the ecological consequences of water hyacinth invasion, highlighting the urgent need for targeted research and intervention strategies to protect and restore affected freshwater ecosystems.

Keywords Water hyacinth · *Eichhornia crassipes* · Invasive species · Freshwater ecosystem · Ecological impacts

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Introduction

The IPBES (2023) defines invasive non-native species as the subset of established non-native species that spread and have negative impacts on biodiversity. Non-native plants that can propagate rapidly and vegetatively have the potential to be invasive non-native plants. Such invasive plants are capable of causing disturbances in ecosystem functioning and nutrient balance (Lansdown et al. 2016). As a particular example, invasive freshwater plants (macrophytes) can degrade water quality by disturbing the flow and altering the primary productivity of the aquatic system (Zenetos et al. 2009). Invasive macrophytes are also known to disrupt irrigation channels, water intakes, and hydroelectric facilities by clogging in and altering the functions of dams and other infrastructures (Spencer and Seaman 1980). Therefore, invasive freshwater plants are causing significant ecological and socio-economic damages (Villamagna and Murphy 2010).

As one of the worst 100 invasive species of the world listed by the IUCN Invasive Species Specialist Group, water hyacinth (*Pontederia crassipes*, used to be *Eichhornia crassipes*), is one of the most noxious freshwater plant invaders (Lowe et al. 2000). Native to South America, the water hyacinth now spreads across 70 countries on five continents (Gezie et al. 2018), with freshwaters in tropical and sub-tropical regions with high concentrations of nutrients due to agricultural runoffs being the most vulnerable to water hyacinth invasions (Villamagna and Murphy 2010). Although the current spread of the species is limited to tropical and subtropical regions, climate change is further expected to trigger its expansion to greater latitudinal zones (Hellmann et al. 2008; Rahel and Olden 2008). Water hyacinth can easily get established in areas lacking sufficient aquatic macrophytes and can replace the native species through competition (Wilson et al. 2005). Furthermore, in the invaded regions, the absence of weevil species (i.e., *Neochetina eichhorniae* and *Neochetina bruchi)* that feed upon water hyacinth in its native habitats further assists this weed in becoming a super spreader (Wilson et al. 2005). After becoming invasive, water hyacinth can cause catastrophic environmental damage (Gezie et al. 2018).

One of the most observed impacts of water hyacinth is their impact on water conditions (Villamagna and Murphy 2010), including dissolved oxygen (Brendonck et al. 2003), temperature, and pH (Giraldo and Garzon 2002). However, the direction and generality of such impacts are still unclear. For example, a review by Villamagna and Murphy (2010) found decreased dissolved oxygen, phosphorous, nitrogen, and phytoplankton production in a freshwater system post-invasion by water hyacinth, reducing habitat heterogeneity and aquatic biodiversity. Studies have also reported an increase in dissolved oxygen (Greenfield et al. 2007) and an increase in temperature (Chapungu et al. 2018; Jagaveerapandian and Thamizharasu 2015; Yongo et al. 2017) caused by water hyacinth invasion. The inconsistent impact of water hyacinth on the freshwaters can be due to varying nutrient levels (Gaikwad and Gavande 2017; Karouach et al. 2022), water flow (Churko et al. 2023; Dersseh et al. 2022), climate conditions (Hellmann et al. 2008), human activities (Dersseh et al. 2022; Karouach et al. 2022), and presence of herbivores (Karouach et al. 2022).

Along with water quality, water hyacinth invasions have significant effects on aquatic biodiversity. As a fast-growing plant that forms dense mats on water surfaces, it alters habitats and disrupts the ecological balance of freshwater ecosystems (Tobias et al. 2019). Aquatic birds are one of the aspects of aquatic biodiversity known to be impacted by water hyacinth invasion. Water hyacinth mats reduce the availability of open water, which is crucial for many bird species for foraging and nesting. Birds that rely on open water for feeding, such as waterfowl and waders, find their habitats reduced, leading to a decline in their populations (Villamagna and Murphy 2010). Dense mats can also prevent some bird species from reaching to their feeding grounds resulting in reduced food availability. Marco et al. (2001) found that bird species diversity and abundance significantly decreased in water bodies heavily invaded by water hyacinth.

Aquatic invertebrates are also found to be impacted by the invasion of this weed. Water hyacinth provides habitat for some invertebrates while being detrimental to others. Invasive macrophytes like water hyacinth can create favorable conditions for invertebrates such as mosquitoes and midges, which thrive in stagnant water with low dissolved oxygen levels (Ofulla et al. 2010). However, not all species of invertebrates benefit from water hyacinth invasion. Crustaceans and other sensitive invertebrate species are adversely affected by reduced oxygen levels and altered water chemistry. Findings of Toft et al. (2003) showed that crustacean diversity and abundance declined in areas invaded by water hyacinth. Water hyacinth invasions thus have complex and far-reaching effects on aquatic biodiversity.

Given the far-reaching ecological and economic consequences of water hyacinth, it is surprising that no systematic review of its impacts on freshwater ecosystems has been conducted. Existing studies often provide fragmented and region-specific insights, making it challenging to draw general conclusions about the global impact of water hyacinth. This gap in the literature hampers the ability to formulate effective management and mitigation strategies on a greater scale. Here, in this meta-analysis, we systematically synthesized data from a diverse array of studies to provide a comprehensive and holistic understanding of water hyacinth invasion on freshwater ecosystems worldwide. We hypothesized that the invasion of water hyacinth would significantly alter water quality and ecological parameters in invaded freshwater ecosystems. Furthermore, this meta-analysis highlights the need for more targeted research in underrepresented areas, guiding future studies to address the existing knowledge gaps.

Methods

Systematic literature search

We followed the standard guidelines (Page et al. 2021; Pullin and Stewart 2006) for systematic search and selection of research works for meta-analysis. We searched the Web of Science, JSTOR, and Scopus between September 25 and October 15, 2024, and identified peer-reviewed original research articles that reported observational or experimental data related to the impact of water hyacinth as a freshwater invader. We used the phrases in combination of (*"Pontederia crassipes"* OR *"Eichhornia crassipes"* OR "water hyacinth") AND (impact* OR effect* OR affect) AND (freshwater OR "fresh water" OR aquatic) AND (physical OR chemical OR biological OR ecosystem OR environment*). The final search based on bibliographies of retrieved articles was made in Google Scholar.

Study selection and data extraction

Our initial search yielded a total of 3390 records. After an initial screening based on titles and abstracts, we identified 139 studies for further review. From these, we excluded 58 studies that did not analyze the impacts of water hyacinth, resulting in a subset of 81 studies. Additionally, we identified 17 more studies through the bibliographies of selected studies, bringing the total to 98 studies for detailed examination.

For these 98 studies, we reviewed the methods and results sections. Only studies that generated original data and included both control and treatment setups were selected for final analysis. A detailed overview of the literature search process is provided in the PRISMA flow diagram, following the guidelines of Page et al. (2021) (Supplementary material, Figure S1).

In total, 25 studies were shortlisted for the meta-analysis. The details of the included studies are included as supplementary material (Table S1). The supplementary data table has an additional study from Brazil that met our requirements. However, as we were interested in investigating the impacts of the weed in invaded range, we did not include that study in our meta-analyses. All of the shortlisted studies reported mean, standard deviation (SD), and sample size for both treatment and control groups. We also included studies that reported standard error (SE) instead of SD, calculating the corresponding SD where necessary. From the final 25 studies, we extracted 16 types of information as outlined in Table 1.

Statistical analysis

Based on the information we extracted from the selected studies, we focused on the impacts of water hyacinth invasion on (1) physical (conductivity, suspended solid, temperature, and turbidity), (2) chemical (dissolved oxygen, nitrogen, phosphate, and pH), and (3) biological (macroinvertebrates) aspects of freshwaters. For simplicity, these nine types of impact under the three broad categories will be referred as 'parameters' from here on. For the final analysis, we only included those parameters investigated in at least five independent studies. We choose this threshold to ensure that the reported results are based on a sufficient level of evidence.

As the same study sometimes reported observations of multiple impacts, we accounted for the non-independence of observations from the same study by fitting a mixed-effects model. We treated different groups of observations within the same study as nested observations and extracted multiple effect sizes from the same study. This structure enabled us to include both study-level and group-within-study-level random effects, ensuring an accurate reflection of the hierarchical structure of our data (Cheung 2019; Habeck and Schultz, 2015). We used the rma.mv function with restricted maximum likelihood

Table 1 Description of information collected from the sorted studies

Data	Description
Author	The name(s) of the author(s) of the study
Year	The year when the study was published
Title	The title of the study
Journal	The name of the journal where the study was published
Time since invasion	Duration since the invasion of water hyacinth began, if applicable
Type of water body	Classification of the water body studied (e.g., river, large reservoir, pond, or experimental water bodies)
Country of study	Country where study was conducted
Study design	Type of study design employed, such as observational study or experimental setup
System studied	The specific ecosystem component studied, such as water quality, invertebrates, phytoplankton, fish, or waterbirds
Impact studied	Under each system studied, various impacts were particularly studied such asunder water quality, studies looked at dissolved oxygen, pH, temperature, nitrites, phosphates, conductivity and many others
Mean (Control)	Mean value in the uninvaded site
SD (Control)	SD of the measured values for the uninvaded site
Sample size (control)	Number of samples for the uninvaded site
Mean (Invaded)	Mean value in the invaded site
SD (Invaded)	SD of the measured values for the invaded site
Sample size (Invaded)	Number of samples for the invaded site

estimation (REML) from the metafor R package (version 4.6; Viechtbauer 2020) to fit the mixed effect model to estimate standardized mean differences (SMD) along with their 95% confidence intervals. SMD, a measure for effect size was calculated using Hedge's *g* (Hedges, 1981; Tasker et al. 2022).

$$SMD = \frac{Treatment\ Mean - Control\ Mean}{Pooled\ StandardError} \times Weighing\ Factor\ (\#of\ Replicates)$$

The resultant Hedge's *g* value is unit less and can range from negative to positive infinity.

We also assessed between-study heterogeneity using the Q and I2 statistics (Harrer et al. 2021). A higher Q value indicates greater heterogeneity not accounted for by the model, while a higher I2 value suggests a larger percentage of variability in effect size due to between-study differences. Generally, an I2 value of 75% or more suggests substantial heterogeneity (Higgins 2003). Additionally, we constructed funnel plots for each outcome variable to explore potential publication bias in our meta-analyses which might arise when studies with significant or favorable results are more likely to be published than studies with non-significant or unfavorable results. By displaying effect size against their standard errors, these plots allow visual inspection of the symmetry of data distribution (Sterne and Egger 2001). All analyses were conducted in R Version 4.4.1 (R Core Team, 2013).

Result

The 25 studies used for our final analyses spread across 12 countries over three continents (Fig. 1). Africa and Asia contributed equal number of studies (n = 11), whereas three studies came from North America. Most studies were on lentic (standing water) water (n = 21). Of these 21 studies, 16 performed experiments/observations in lakes, reservoirs, or ponds. Whereas the remaining five were either mesocosms or experimental ponds-based studies. The remaining four water bodies were lotic (free-flowing) systems such as rivers, estuaries, or lagoons.

Across nine parameters, these 25 studies contributed to 246 effect sizes (Fig. 2). Our meta-analysis showed a decreasing trend for five out of nine

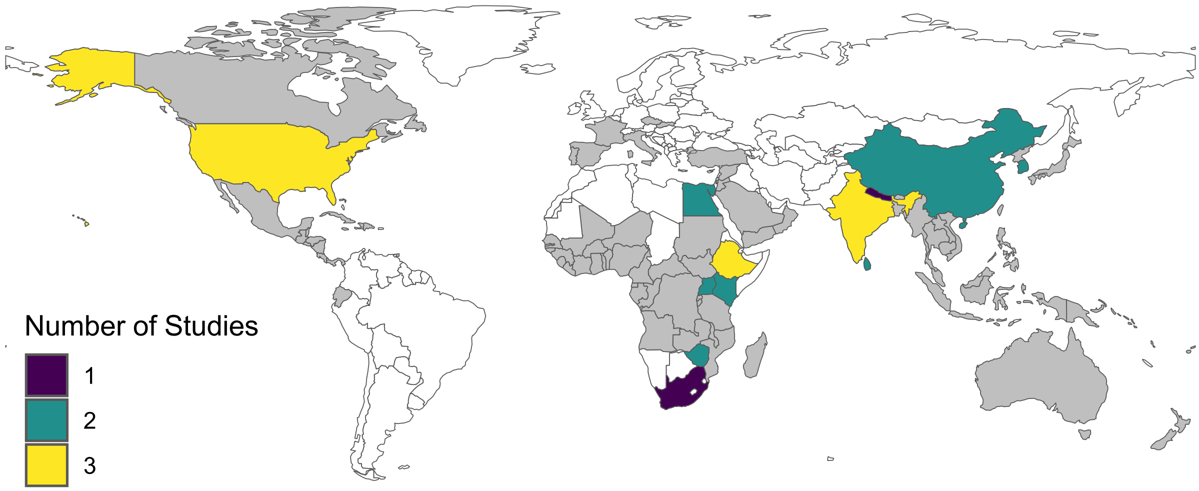

Fig. 1 Number of studies from representative countries included in our meta-analysis. The gray countries indicate water hyacinth's introduced region (*Source* https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:310928-2)

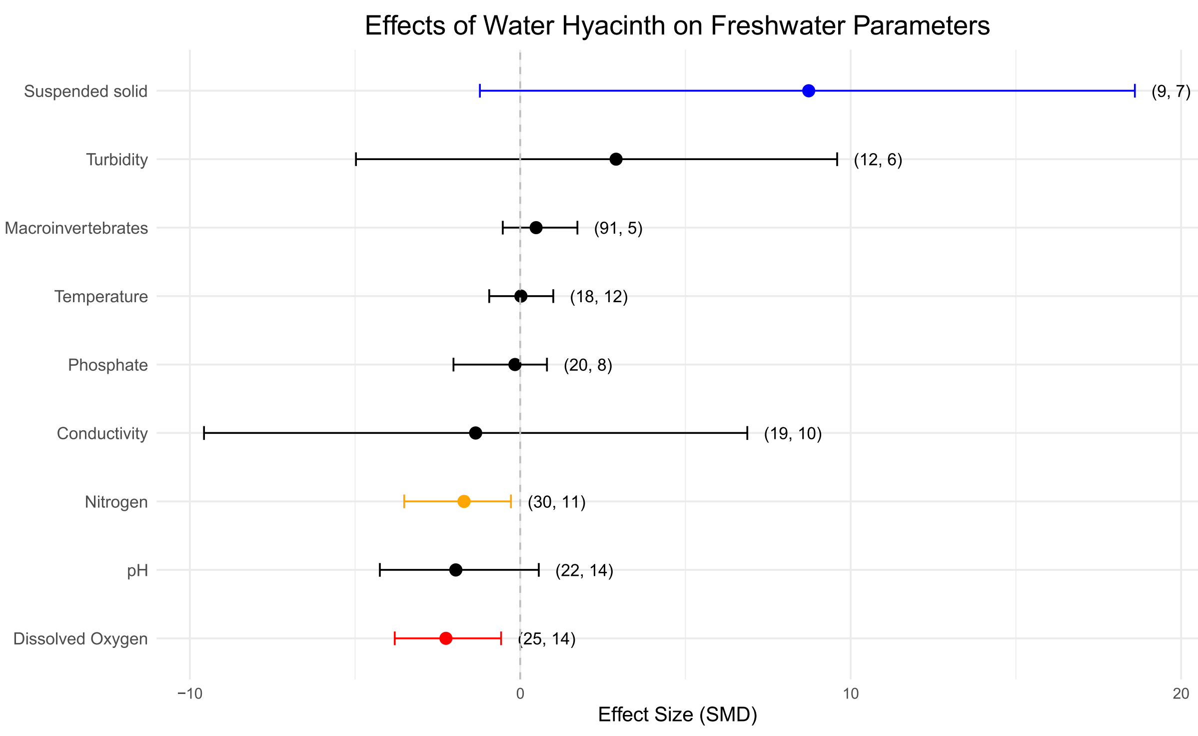

Fig. 2 Standardized Mean difference (SMD) between treatment and control, showing the effects of invasive water hyacinth on nine parameters that describe water quality and biodiversity. The values in parentheses (**a**, **b**) represent: **a** the total number of effect sizes used in the model; **b** the total number of unique articles that contributed to the effect sizes. The size of the bars represents 95% Confidence Intervals (CI). The different colors (red, orange, blue, black) of effect size bars represent different levels of significance; the red colored bar indicates a highly significant effect (**; $p<0.001$); the orange colored bar indicates a significant effect (*; $p<0.01$); the blue colored bar indicates a marginally significant effect (.; $p<0.1$); the black colored bars indicate non-significant effects

parameters (Table 2). The most prominent and significant effect was on dissolved oxygen (estimate SMD = −2.26, 95%, CI: [−3.94, −0.56], $p = 0.001$) and nitrogen (SMD = −1.70, 95%, CI: [−3.19, −0.20], $p = 0.01$). Other non-significant but negative trends were noticed for phosphate, conductivity, and pH. We observed non-significant positive trends for temperature, suspended solid, and turbidity (Fig. 2, Table 2). For eight out of nine models, I^2 value which reflects the level of heterogeneity was beyond 75% indicating a large portion of residual variation remained unexplained (Table 2). However, for macroinvertebrates, the I^2 value was relatively lower at 73.23%, suggesting moderate heterogeneity indicating more consistent effect size across studies for macroinvertebrates.

Top three parameters reported in multiple studies (total 25) were dissolved oxygen (n = 14), temperature (n = 12), and pH (n = 14). For dissolved oxygen, we observed decreasing trend between control and invaded freshwater ecosystems for most studies (Fig. 3, left panel). This pattern is well summarized in the parameter estimation for dissolved oxygen (Table 2). For temperature, we noticed both increasing and decreasing pattern post invasion (Fig. 3, middle panel), which led to a non-significant but overall marginal increasing pattern (estimate SMD = 0.02, 95% CI = [−0.9, 0.96], $p = 0.58$) (Table 2). Similarly, we also noticed decreasing trend of pH for more than two-third of studies that were incorporated in our meta-analysis. However, there were a few studies which showed an increasing trend. Interestingly, we observed a steep increase in pH in a few sites (Fig. 3, right panel). The parameter estimation reflected the same with non-significant decreasing value (estimate SMD = −1.95, 95% CI = [−4.35, 0.45], $p = 0.13$; Table 2).

We created a funnel plot to assess the potential publication bias across the studies included in our meta-analysis (Fig. 4). The plot shows some degree of asymmetry, particularly with an outlier towards right (SMD ≈ 9) for suspended solid which has large effect size and higher standard error. Additionally, significant effects (red and orange points) are clustered to the left of the zero line, representing significantly negative impacts of water hyacinth. The concentration of these points on one side of the funnel suggests that studies with significant negative effects might be overrepresented, potentially indicating publication bias or small study effects. This asymmetry may be reflecting a bias toward publishing studies with significant or more extreme results. However, despite these observations, the general spread of the points across both sides of the zero line provide some balance in the overall dataset.

Discussion

Our review and meta-analysis showed a surprising lack of studies exploring the impact of water hyacinth as a freshwater invader. Although water hyacinth is invading over 70 countries, we could only find 25

Table 2 Standardized mean differences (SMD) estimates from multilevel mixed-effect models of the impacts of water hyacinth on eight parameters that describe water quality and biodiversity

Parameter	SMD ± CI95	Significance	Number of effect Sizes	Number of studies	Heterogeneity statistics
Dissolved oxygen	−2.1927 ± 1.60	**	25	14	Q = 553.26, df = 24, $p < 0.0001$; $I^2 = 95.66\%$
Temperature	0.037 ± 0.9845	ns	18	12	Q = 144.80, df = 17, $p < 0.0001$; $I^2 = 88.26\%$
Nitrogen	−1.8909 ± 1.6142	*	30	11	Q = 321.37, df = 29, $p < 0.0001$; $I^2 = 90.99\%$
Phosphate	−0.6067 ± 1.4154	ns	20	8	Q = 295.65, df = 19, $p < 0.0001$; $I^2 = 93.56\%$
Suspended Solid	8.6903 ± 9.9125		9	7	Q = 182.72, df = 8, $p < 0.0001$; $I^2 = 95.62\%$
macroinvertebrates	0.6029 ± 1.1304	0.456	91	5	Q = 336.35, df = 90, $p < 0.0001$; $I^2 = 73.23\%$
Conductivity	−1.3495 ± 8.22	ns	19	10	Q = 495.19, df = 18, $p < 0.0001$; $I^2 = 96.36\%$
pH	−1.847 ± 2.4025	ns	22	14	Q = 425.12, df = 21, $p < 0.0001$; $I^2 = 95.6\%$
Turbidity	2.2661 ± 7.2384	ns	12	5	Q = 320.07, df = 11, $p < 0.0001$; $I^2 = 96.56\%$

SMD represents Standardized Mean Difference (Hedge's g) of treatment and control group. CI95 is 95% Confidence Intervals. Q along with its associated p-value and I^2 give an estimation of residual heterogeneity. An I^2 value of 75% or more indicates considerable heterogeneity. $0.05 < p < 0.1$, $*p < 0.01$, $**p < 0.001$

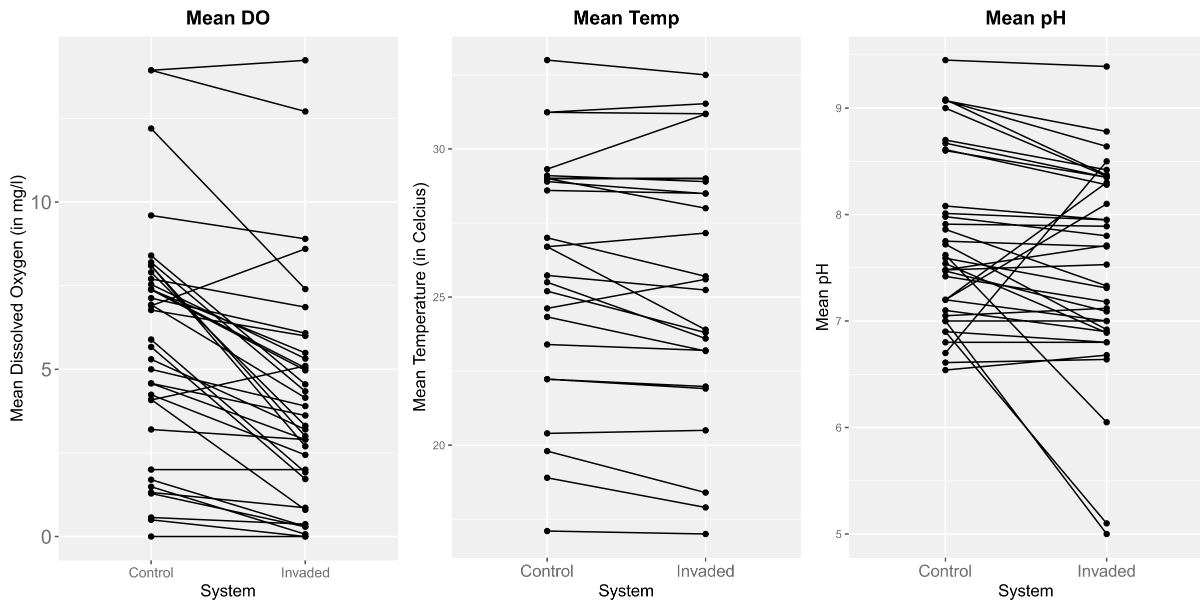

Fig. 3 Differences in mean dissolved oxygen (DO), temperature, and pH (going from left to right) between control plots and plots with invasive water hyacinth. X-axis denotes two groups as control and invaded and Y-axis denotes the mean dissolved oxygen (in mg/l), mean temperature (in Celsius), and mean pH for the first, second, and third panel respectively

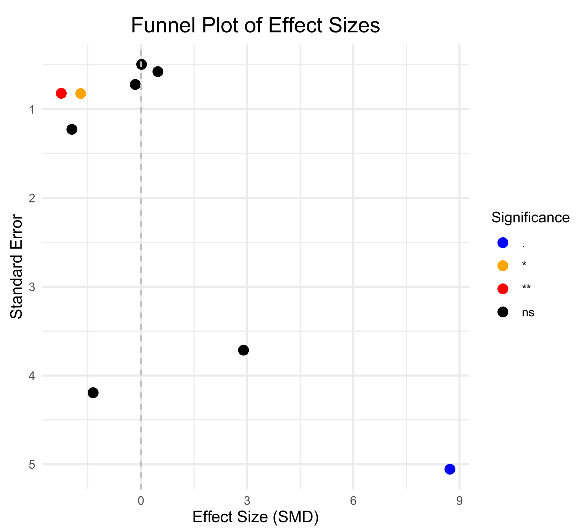

Fig. 4 Funnel plot assessing potential publication bias in the meta-analysis of water hyacinth impacts on freshwater parameters. The plot displays standardized mean differences (SMD) of effect sizes on the x-axis against their standard errors on the y-axis. Each point represents an effect size from a study, with colors indicating significance levels (black = non-significant, red = $p < 0.01$, orange = $p < 0.05$, blue = $p < 0.1$)

studies distributed over 12 countries that compared the impact water hyacinth invasion with control. However, this can be a global trend of less studies being conducted for this ecosystem. A recent global meta-analysis exploring the impacts of multiple freshwater invasive macrophytes also reported only 53 articles (Tasker et al. 2022).

Our study showed significant reductions in dissolved oxygen and nitrogen due to water hyacinth invasion, indicating a plausible indirect impact on aquatic ecosystems. Seven out of nine type of impacts we studied had inconsistent pattern in the impacts of water hyacinth. The observed heterogeneity across studies highlights the context-dependent nature of these impacts, emphasizing the need for targeted management. Such inconsistency in results aligns with the uncertain and complex nature of freshwater ecosystem. Variables such as climate and water conditions, nutrient abundance, presence of other macrophytes, and management efforts associated with freshwater ecosystems vary from place to place (Reitsema et al. 2018), influencing the intensity of water hyacinth invasion. As a natural result, the impacts of water hyacinth vary from site to site (Corman et al. 2023).

This meta-analysis shows an overall significant decrease in dissolved oxygen in a freshwater body after being invaded by water hyacinth, which is consistent with other studies (Wilson et al. 2005). Several reasons can explain this pattern. First, growing leaves and stems of water hyacinth can consume the available oxygen in the water for respiration, and the decaying matter of dead water hyacinth also consumes oxygen. Second, water hyacinth can block the light, preventing phytoplankton and submerged vegetation from getting enough energy require for photosynthesis, thus reducing the amount of oxygen produced (Wilson et al. 2005). These consequences in combination decrease the amount of dissolved oxygen in the invaded system.

Along with this, our meta-analysis also indicated a consistent decreasing nitrogen level in water bodies post water hyacinth invasion. Earlier similar work also reported decrease in nitrogen in water hyacinth invaded area (Villamagna and Murphy 2010). This trend reflects water hyacinth efficiency of up taking of nitrogen for its rapid growth and thus reducing the available nitrogen in the water body (Reddy and De Busk, 1985). Additionally, the dense mats of water hyacinth might create anaerobic conditions favoring denitrification, leading to further nitrogen loss (Jia et al. 2023). These ecological processes might be playing a major role in depleting nitrogen.

Furthermore, although non-significant, we observed a marginal increase in water temperature post invasion. Despite the fact that mat-like root structure of water hyacinth can prohibit penetration of sunlight below water surface and thus keep water at lower temperature (Tobias et al. 2019), there are several studies which also claim water temperature to rise after water hyacinth invasion (Chapungu et al. 2018; Jagaveerapandian and Thamizharasu 2015; Yongo et al. 2017).

Additionally, we found non-significant but decreasing pattern for the pH of water post invasion. This fluctuation in water pH can happen in multiple ways. First, water hyacinth can consume the nutrients like nitrogen and phosphorus from the water resulting in the reduction of nutrient. The reduction in the nutrients can lead to reduction in the carbonates in the water which results in lower pH for water (Giraldo and Garzon 2002). Water hyacinth can also alter water pH through the substances it produces. For example, the mucilage it produces can coat the surface of water and the plant itself. This mucilage can absorb and release carbon dioxide from water, which alerts the pH level. Similarly, water hyacinth can release volatile organic compounds into the water, altering the water pH level (Giraldo and Garzon 2002).

Our result regarding the abundance of macroinvertebrates is in line with a global pattern where water hyacinth favors some macroinvertebrates while it is detrimental for others (Marco et al. 2001). Macroinvertebrates like mosquito, midges, and snails are expected to increase in habitat with water hyacinth (Ofulla et al. 2010) whereas crustaceans do not prefer habitat with water hyacinth (Toft et al. 2003). Although not included in this meta-analysis because of insufficient studies, one study that investigated impacts of water hyacinth invasion on waterbirds abundance reported decreasing trend for all the species (Sinha et al. 2011). As most birds prefer macroinvertebrates as diet, decrease in macroinvertebrates might have cascading effect on the bird abundance in the freshwater with water hyacinth. Similarly, two studies (Ngodigha 2024; Zhao and Chen, 2016) which explored the impacts of water hyacinth on phytoplankton abundance reported a consistent decreasing trend.

Along with this, there can be other various impacts of water hyacinth on biodiversity due to cascading effects of the hyacinth on water quality. Decrease in dissolved oxygen, temperature, and pH of water are factors which largely influences aquatic biodiversity of the system. As species have their tolerance limit for dissolved oxygen, temperature, and pH, the alteration in these parameters may cause shift in species distribution. This may lead to higher abundance of some species which are tolerant to low dissolved oxygen, temperature and pH and disappearance of some species which are intolerant to these changes. These shift in species composition can alter the species distribution between different layers of freshwater which can have several adverse impacts on food webs of the freshwater ecosystem (Meerhoff et al. 2003). The shift in invertebrate community composition can have cascading effects on the food web. Birds that rely on certain invertebrates for food might find their primary food sources diminished, leading to broader ecological impacts (Marco et al. 2001). Decrease in temperature may impact the migration pattern of some species of fish as they depend on certain temperature to trigger migration (Fenkes et al. 2016; Salinger and Anderson 2006). The disruption in migration pattern may threat the existence of species as such migrations are part of their life cycle (Tamario et al. 2019).

Conclusion

Our meta-analysis provides valuable insights into the impacts of water hyacinth invasion on multiple factors, though we acknowledge that our results were based on a limited number of studies. On one hand, our results highlight consistent trends such as the decrease in dissolved oxygen and nitrogen; on the other hand, we reveal areas with inconsistent results, emphasizing the need for more studies. This study also points out the importance of strategic planning in identifying key geographical regions where further studies are crucial to achieve a more comprehensive understanding of water hyacinth's ecological effects.

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Author contribution Both authors contributed to the study's conception and design. Data collection and analysis were performed by Rohit Raj Jha. The first draft of the manuscript was written by Rohit Raj Jha and Both authors edited all versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated and analyzed for this manuscript will be made available in the Dryad open access data repository.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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