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Ultrasonic control of aquatic macrophytes in reservoirs: An integrated review

Controle ultrassônico de macrófitas aquáticas em reservatórios: Uma revisão integrada

Control ultrasónico de macrófitas acuáticas en embalses: Una revisión integrada

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Abstract

The excessive proliferation of cyanobacteria and aquatic macrophytes in water reservoirs has been a concern for governments, energy companies managing hydroelectric and thermal power plants, and local populations. These aquatic organisms, when overabundant, negatively impact the management of water for public supply and energy generation, obstructing intake systems and damaging water treatment stations. Ultrasound emerges as a potential technique for controlling these organisms. The aim of this study was to perform an integrative review by selecting articles published between 2020 and 2024, focusing on the efficacy and ecological implications of ultrasonic control on these aquatic populations. The methodology involved searching scientific databases, selecting 14 articles out of a total of 42, based on their relevance to the theme of ultrasonic control and its practical applicability. The results indicate that ultrasonic frequencies of 20 kHz collapsed gas vacuoles in these aquatic organisms within 40 seconds of exposure, demonstrating the potential application of this technique in controlling these organisms, although it is necessary to adjust the intensity according to the specific environmental conditions of the reservoir and the biology of the target organisms. However, exposure to ultrasound can release toxins, affect non-target organisms, and alter the aquatic community structure, resulting in negative impacts such as hypoxia and fish death. It highlights the need to adopt an adaptive model to adjust ultrasound parameters and integrate them with other management practices. The study emphasizes the importance of conducting laboratory-scale tests and continuous monitoring to optimize efficacy and minimize environmental risks. Future development of more efficient and less invasive ultrasonic transducers is also recommended, as well as interdisciplinary collaboration to promote more sustainable reservoir management.

Keywords: Ultrasonic waves; Acoustic cavitation; Floating macrophytes; Cyanobacteria; Sustainability.

Resumo

A proliferação excessiva de cianobactérias e macrófitas aquáticas nos reservatórios de água tem sido motivo de preocupação dos governos, empresas de energia gestoras de hidrelétricas e termoelétricas, e da população do entorno. Esses organismos aquáticos quando em excesso impactam negativamente a gestão de águas para abastecimento público e geração de energia, obstruindo sistemas de captação e prejudicando estações de tratamento de água. O ultrassom surge como uma potencial técnica para o controle desses organismos. O objetivo do estudo foi realizar uma revisão integrativa através da seleção de artigos publicados entre 2020 e 2024, focando na eficácia e implicações ecológicas do uso do controle ultrassônico sobre estas populações aquáticas. A metodologia envolveu a busca em bases de dados científicas, selecionando 14 artigos de um total de 42, com base em sua relevância para o tema do controle ultrassônico e sua aplicabilidade prática. Os resultados indicam que frequências ultrassônicas de 20 kHz colapsaram vacúolos de gás presentes nesses organismos aquáticos em 40 segundos de exposição à radiação, mostrando um potencial de aplicação desta técnica no controle desses organismos, embora seja necessário ajustar a intensidade de acordo com as condições ambientais específicas do reservatório e a biologia dos organismos alvo. Entretanto, a exposição ao ultrassom pode liberar toxinas, afetar organismos não-alvo e alterar a estrutura comunitária aquática, resultando em impactos negativos como hipoxia e morte de peixes. Destaca-se a necessidade de adotar um modelo adaptativo para ajustar os parâmetros de ultrassom e integrá-los a outras práticas de gestão. O estudo enfatiza a importância de realizar testes em escala laboratorial e monitoramento contínuo para otimizar a eficácia e minimizar os riscos ambientais. Recomenda-se também o desenvolvimento futuro de transdutores ultrassônicos mais eficientes e menos invasivos, e a colaboração interdisciplinar para promover um manejo mais sustentável dos reservatórios.

Palavras-chave: Ondas ultrassônicas; Cavitação acústica; Macrófitas flutuantes; Cianobactérias; Sustentabilidade.

Resumen

La proliferación excesiva de cianobacterias y macrófitas acuáticas en los embalses de agua ha sido motivo de preocupación para los gobiernos, empresas de energía gestoras de centrales hidroeléctricas y termoeléctricas, y la población circundante. Estos organismos acuáticos, cuando están en exceso, impactan negativamente en la gestión del agua para abastecimiento público y generación de energía, obstruyendo los sistemas de captación y dañando las estaciones de tratamiento de agua. El ultrasonido surge como una técnica potencial para el control de estos organismos. El objetivo de este estudio fue realizar una revisión integrativa mediante la selección de artículos publicados entre 2020 y 2024, centrándose en la eficacia y las implicaciones ecológicas del uso del control ultrasónico sobre estas poblaciones acuáticas. La metodología involucró la búsqueda en bases de datos científicas, seleccionando 14 artículos de un total de 42, basándose en su relevancia para el tema del control ultrasónico y su aplicabilidad práctica. Los resultados indican que las frecuencias ultrasónicas de 20 kHz colapsaron los vacuolos de gas presentes en estos organismos acuáticos en 40 segundos de exposición a la radiación, mostrando un potencial de aplicación de esta técnica en el control de estos organismos, aunque es necesario ajustar la intensidad según las condiciones ambientales específicas del embalse y la biología de los organismos objetivo. Sin embargo, la exposición al ultrasonido puede liberar toxinas, afectar a organismos no objetivo y alterar la estructura comunitaria acuática, resultando en impactos negativos como hipoxia y muerte de peces. Se destaca la necesidad de adoptar un modelo adaptativo para ajustar los parámetros de ultrasonido e integrarlos con otras prácticas de gestión. El estudio enfatiza la importancia de realizar pruebas a escala de laboratorio y monitoreo continuo para optimizar la eficacia y minimizar los riesgos ambientales. También se recomienda el desarrollo futuro de transductores ultrasónicos más eficientes y menos invasivos, y la colaboración interdisciplinaria para promover una gestión más sostenible de los embalses.

Palabras clave: Ondas ultrasónicas; Cavidad acústica; Macrófitas flotantes; Cianobacterias; Sostenibilidad.

1. Introduction

Reservoirs, semi-artificial bodies of water located between rivers and lakes, play critical roles for ecosystems and human activities. They are essential for water storage, irrigation, flood control, potable water supply, energy generation, recreation, and biodiversity conservation (Xu et al., 2024; Ye et al., 2017). Moreover, these aquatic environments are sensitive indicators of ecosystem changes, reflecting watershed quality through the dynamics of phytoplankton and zooplankton communities (Tao et al., 2024). However, human intervention and the exploitation of natural resources have exacerbated nutrient loads in these reservoirs, fostering excessive proliferation of cyanobacteria and aquatic plants (macrophytes), as they act as indicators of water pollution due to their sensitivity to changes in the chemical composition of the aquatic environment.

They absorb nutrients and chemicals from the water, which makes them capable of reflecting the level of pollution and the presence of nutrients like nitrogen and phosphorus (Córdova et al., 2024; X. Li et al., 2023; Sayanthan et al., 2024).

Macrophytes can indicate the eutrophic state of a water body, based on their rapid growth in response to increased nutrient levels from sources such as agricultural fertilizers, and domestic and industrial effluents. Additionally, the composition of macrophyte communities can provide information about the presence of specific pollutants, salinity, and pH conditions. Thus, macrophytes are valuable indicators for environmental monitoring and assessing the health of aquatic ecosystems (Huisman et al., 2018; Rocha et al., 2018; Sompura et al., 2024; Y. Yang & Liu, 2023).

Although aquatic macrophytes are essential for ecology due to their roles in photosynthesis, nutrient cycling, and as habitats for various species, they become problematic when their proliferation is uncontrolled (Zhang et al., 2024). This unchecked growth is often attributed to human interventions, including agricultural practices and improper waste disposal, leading to serious environmental issues such as decreased oxygen availability in the water and compromised water quality. Excessive growth of these plants can also have adverse economic and ecological impacts, interfering with activities such as hydropower production (de Paula et al., 2024), chemical consumption for water treatment (Baydum et al., 2018), recreational activities, and flood management (Bai et al., 2020).

In light of this situation, there is a need to explore environmentally sustainable and efficient control methods. While conventional physical, chemical, and biological methods of controlling macrophyte proliferation are widely used, they have significant limitations, including negative impacts on aquatic biodiversity and high operational costs (Hussner et al., 2017). In this context, ultrasonic control, which uses high-frequency sound waves (20 kHz and higher), emerges as a promising alternative. This method offers the advantage of being less invasive and potentially more sustainable, minimizing impacts on the aquatic ecosystem, especially due to the short application time required (Akinnawo, 2023; Alahuhta et al., 2018; Bermarija et al., 2022; Karouach et al., 2022; L. Li et al., 2023; Misteli et al., 2023; Moura Júnior et al., 2018; Sobral & Santos, 2023; Souza et al., 2020; Wang et al., 2023; WU & WU, 2007; Zhao et al., 2012).

This study aims to evaluate the efficacy and ecological implications of ultrasonic control of cyanobacteria and aquatic macrophytes in reservoirs, using an integrative review methodology. The research was conducted through a systematic search in the Web of Science and PubMed databases, accessible via the CAPES periodicals portal, covering publications from 2020 to 2024. A total of 14 articles were meticulously selected from 42 available, based on stringent criteria such as: articles in English, peer-reviewed, and directly relevant to the use of the ultrasound in controlling cyanobacteria and macrophytes. The integrative review will not only identify and understand the potential of the ultrasound as an effective strategy but also develop environmentally responsible and efficient control approaches. This effort is aimed at improving water quality in reservoirs, preserving aquatic biodiversity, and promoting the sustainability of water resources, fostering more integrated and sustainable management practices that combine ultrasound with other control strategies for optimized management of aquatic ecosystems in reservoirs.

2. Methodology

This study adopted an integrative literature review methodology to evaluate the efficacy and ecological implications of using ultrasonic control on cyanobacteria and aquatic macrophytes in reservoirs. The integrative review allows for the systematic inclusion of both experimental and non-experimental studies, providing a comprehensive understanding of the subject under investigation, synthesizing existing knowledge, and identifying gaps for future research (Botelho et al., 2011; Camargo Júnior et al., 2023).

The guiding question for this review was: "What is the efficacy of ultrasonic control in managing cyanobacteria and aquatic macrophytes in reservoirs, and what are its ecological implications?"

The research was conducted using relevant scientific databases, including PubMed and Web of Science. The search terms used were: "ultrasound", "ultrasonic control", "cyanobacteria", "aquatic macrophytes", "management of aquatic reservoirs". Article selection was based on stringent criteria such as: articles published in English between 2020 and 2024; peer-reviewed; and directly relevant to the use of ultrasound in controlling cyanobacteria and macrophytes.

Studies that addressed the use of ultrasonic control in aquatic environments, specifically for managing cyanobacteria and macrophytes, were included. Articles that did not directly deal with ultrasonic control or that were literature reviews without primary data were excluded.

Data were extracted from each selected article, including author(s), year of publication, study objectives, methodology, main results, and conclusions. This information was used to synthesize relevant findings related to the efficacy and ecological implications of ultrasonic control.

The quality of the included studies was assessed based on specific criteria for experimental and observational studies, considering the study design, clarity of result presentation, and the relevance of findings to the practice of controlling cyanobacteria and macrophytes.

The results of the studies were qualitatively analyzed to identify trends, commonalities, and discrepancies in the findings. This analysis highlighted the efficacy of ultrasonic control and its potential implications for the sustainability of aquatic ecosystems.

This methodology enabled a comprehensive and detailed assessment of the use of ultrasound in controlling cyanobacteria and aquatic macrophytes, contributing to the scientific knowledge base and informing environmental management practices.

3. Literature Review

3.1 Ecology of Floating Macrophytes

Aquatic macrophytes are plants that live in aquatic environments such as lakes, rivers, swamps, and estuaries. They can be found floating freely, submerged, or rooted at the bottom of water bodies. They play important ecological roles by providing oxygen through photosynthesis, serving as habitat for other species, and assisting in water purification by absorbing nutrients and heavy metals (Couto et al., 2022).

Aquatic macrophytes are vital components of aquatic ecosystems, crucial in nutrient cycling and promoting primary productivity, helping to maintain ecological balance by absorbing and recycling nutrients. Moreover, they significantly contribute to aquatic biodiversity, serving as habitat and refuge for a wide range of organisms, including birds, fish, and insects. They also play a crucial role in protecting stream banks from erosion and adding essential organic matter to the water, thus enhancing the overall quality of the aquatic ecosystem (Alahuhta et al., 2017; Rocha et al., 2018).

However, despite their numerous ecological benefits, macrophytes can become problematic under certain conditions, especially when influenced by human activities. Overgrowth of macrophytes can lead to environmental problems such as reduced diversity of aquatic flora and fauna, disease proliferation, diminished water quality, and negative impacts on recreational activities, navigation, and energy generation. Therefore, careful management of these organisms is essential to ensure their benefits are maximized while potential adverse impacts are mitigated, highlighting the complexity of their role in aquatic ecosystems (Calvo et al., 2019; dos Santos et al., 2020; Gentilin-Avanci et al., 2021).

There is a variety of macrophytes that adapt to different aquatic environments, from saltwater in marine ecosystems to freshwater environments in lakes, ponds, and rivers. A study conducted in Lake Manzala in Egypt recorded eleven species of aquatic macrophytes, including *Potamogeton pectinatus*, *Eichhornia crassipes*, *Pistia stratiotes*, *Phragmites australis*, *Typha domingensis*, and *Echinochloa stanina* (Esiukova et al., 2021; Haroon, 2022).

The Electric Company of Minas Gerais (CEMIG) also conducted a survey of macrophyte species occurring in Brazilian hydroelectric reservoirs, which is presented in Table 1.

Table 1 - Species of macrophytes found in Brazilian hydroelectric reservoirs.

Família	Nome científico	Nome comum	Hábito	Habitat	Características	Distribuição
ARACEAE	*Pistia stratiotes* L.	Alface-d'água	Free-floating herb; annual or perennial	Calm or slow-moving water, often fully covered on the surface and located in wind-protected areas.	Spongy leaves, up to 30 cm, sensitive to cold, reproduces by seeds or stolons, used for fodder and ornamentation, but can invade and become weedy in wet areas.	Pantropical
COMMELINACEAE	*Commelina diffusa* Burm.f.	Trapoeraba	Amphibious and emergent herb	Prefers moist regions along drainage canal margins.	Weed in fertile and semi-shaded soil, reproduces by seeds or stems, used in animal feed.	Frequent throughout the country
CYPERACEAE	*Eleocharis mínima* Kunth	Tiririca	Aquatic plant that can be submerged, emergent, or amphibious, with a perennial or annual life cycle, depending on water level.	Rivers and lakes	Varies in size; reaches 15-25 cm submerged, and 5-10 cm in wet areas. Serves as food for aquatic and terrestrial animals, and is used as aquarium ornament.	Tropical America
CYPERACEAE	*Rhynchospora corymbosa* (L.) Britton	Capim-navalha	Amphibious or emergent herb; perennial	Wetland zones, common in marshes.	Tufted plant with triangular stem, cutting leaves, rough corymb inflorescence, reproduces by seeds or division. Food for capybaras and invader in wet areas.	Pantropical
LYTHRACEAE	*Cuphea melvilla* Lindl	Sete-sangrias	Perennial, sparsely branched plant that can be amphibious or emergent.	Riverbanks, moist and shaded habitats.	Ornamental plant with rough leaves and red flowers 2.5 to 3 cm.	Tropical, all of Brazil
ONAGRACEAE	*Ludwigia leptocarpa* (Nutt.) H.Hara	Cruz-de-malta	Aquatic herbaceous or subshrub plant, perennial or annual, can be emergent or amphibious.	Aquatic or moist, sunny environments, including fields, riverbanks, and floating islands of aquatic plants.	Plant that appears after floods, with invasive potential. Reproduces by seeds and stem rooting, used as animal forage.	From the southwestern USA to Argentina; also in Africa
ONAGRACEAE	*Ludwigia octovalvis* (Jacq.) P.H.Raven	Cruz-de-malta	Aquatic herbaceous or subshrub plant, perennial or annual, can be emergent or amphibious.	Lakes and rivers	Up to 120 cm, with solitary yellow flowers, spongy roots, and reddish young branches. Grows in moist or flooded soils, reproduces by seeds, thrives in disturbed environments.	Pantropical
ONAGRACEAE	*Ludwigia peploides (Kunth) P.H. Raven*	Cruz-de-malta	Perennial aquatic plant that can be amphibious, submerged, emergent, or fixed floating.	Develops in mud, on the water surface, or on floating islands formed by other macrophytes.	Ornamental plant with variable appearance, leaves change shape and size depending on the environment. Reproduces by seeds, rhizomes, or rooting at nodes, and grows rapidly in disturbed environments.	Pantropical
POACEAE	*Urochloa arrecta (Hack. Ex T.Durand & Schinz) Morrone & Zuloaga*	Braquiária-do-brejo	Amphibious, emergent perennial herb.	Lakes, rivers, and reservoirs	An invasive stoloniferous species from Africa, introduced to Brazil as fodder. It has robust, purplish stems, spreads quickly in moist areas and along watercourses, and can reach up to 120 centimeters in height, currently causing problems in aquatic communities and in hydropower production.	Pantropical

PONTEDERIACEAE	*Eichhornia azurea (Sw.) Kunth*	Aguapé	Emergent, fixed-floating perennial herb.	Lakes, rivers, and floodplain fields	Rhizomatous plant that can grow up to 8 meters. Serves as habitat for insects and fish, and forage for capybaras. Propagates by seeds and rhizomes, showing vigorous growth. Differs from Eichhornia crassipes by having fringed petal margins.	Tropical and subtropical America
PONTEDERIACEAE	*Eichhornia crassipes (Mart.) Solms*	Aguapé	Free-floating or fixed-floating perennial herb in shallower waters.	All water bodies	Native to the Amazon, it reproduces easily vegetatively, by rhizomes or fragments, and its seeds can survive submerged for about 15 years. Feared in disturbed locations due to its rapid proliferation and associated problems.	Native to tropical South America and introduced on all continents
POLYGONACEAE	*Plygonum ferrugineum Wedd*	Erva-de-bicho	Amphibious emergent or floating perennial herb.	Found along riverbanks and in areas with little shade, often growing on floating islands formed by other macrophyte species.	Described plant can reach 2.5 meters in height, being the largest in its genus. It is a pioneer species that propagates by seeds, seedlings, or pieces that root at nodes, and colonizes moist riverbanks in sedimentation areas.	Tropical America
POLYGONACEAE	*Polygonum punctatum* Elliott	Erva-de-bicho	Amphibious, emergent; perennial	Abundant along pond edges, marshes, and floodplains.	Plant has lance-shaped leaves and stems that vary from light green to reddish. Propagates through seeds, fragmentation, or rooting of nodes when they touch the ground.	Throughout Brazil
RUBIACEAE	*Diodia saponariifolia* (Cham. E Schltdl.) K. Schum	Poaia-do-brejo	Amphibious; perennial	Typical of waterlogged terrains, found along riverbanks and ponds.	A creeping, unbranched species with cylindrical stems 50 to 100 centimeters long. Propagates by seeds and dominates areas with its rooted stems.	Occurs in Bahia and the South, Southeast, and Central-West regions
SALVINIACEAE	*Salvinia auriculata* Aubl	Orelha-de-onça	Free-floating herb; annual or perennial	Found in still water springs and slow-moving channels, usually in areas protected from wind.	Propagates vegetatively through offshoots or spores, forming infestations in disturbed environments, covering aquatic surfaces, blocking sunlight, and impacting aquatic ecosystems. Provides forage and habitat for capybaras, insects, birds, snails, and fish.	North and Northeast regions

Source: Brasil (2021).

Regarding their biology, macrophytes can reproduce sexually through seed production and asexually through rhizomes, stolons, or fragmentation. Macrophytes have special adaptations in their tissues, such as aerenchyma, which allows them to float and facilitates gas exchange in aquatic environments. Aerenchyma is a type of plant tissue that features enlarged intercellular spaces, enabling efficient gas diffusion within the plant, such as oxygen. This is particularly important for plants growing in environments where oxygen may be limiting, like aquatic habitats (Björn et al., 2022).

Macrophytes are aquatic plants that grow in or near water, visible to the naked eye. They play crucial roles in aquatic ecosystems and are used as indicators of water quality in many parts of the world. The classification of aquatic macrophytes according to their biological form is presented in Table 2.

Table 2 - Classification of aquatic macrophytes according to their biological form.

Classification	Description
Amphibious	Capable of living both in waterlogged areas and out of water, often changing morphology from aquatic to terrestrial as water levels drop.
Emergent	Rooted in sediment, with parts submerged and others emergent.
Fixed Floating	Rooted in sediment with floating leaves.
Free Floating	Not rooted in sediment, can be carried by water currents, wind, or even animals.
Fixed Submerged	Rooted in sediment, with stems and leaves submerged, generally with flowers emerging above the water.
Free Submerged	Not rooted in the bottom, entirely submerged, generally only flowers emerge.
Epiphyte	Occurring on other aquatic plants.

Source: Björn et al. (2022); USA (2021); Ma et al. (2021).

3.2 Description of Floating Macrophytes and Their Ecological Role

Floating macrophytes play essential ecological functions in aquatic environments. They serve as habitat and food sources for various organisms, such as fish, insects, and microorganisms, providing shelter and nutrition. As significant primary producers, macrophytes perform photosynthesis, converting solar energy into chemical energy, vital for the ecosystem. They also contribute substantially to water quality regulation by filtering pollutants and excess nutrients, which helps maintain the health of the aquatic ecosystem. The roots of macrophytes also play a crucial role in sediment stabilization, preventing erosion. These plants are key actors in the nutrient cycle, facilitating the recycling and balance of nutrients in the aquatic environment (Lesiv et al., 2020; Revéret et al., 2023).

3.3 Negative Impacts of Excessive Proliferation

The excessive proliferation of floating macrophytes can cause serious social, economic, and environmental impacts. Environmentally, in ecosystems where these species are overly abundant, reduced light penetration can hinder the photosynthesis of submerged plants and affect food chains. Additionally, the decomposition of large amounts of macrophytes can lead to oxygen depletion in the water, resulting in fish kills and other impacts on aquatic life. This alteration also directly affects biodiversity and aquatic habitats, impacting ecosystem structure and function (Kumar et al., 2022; Poveda, 2022; Wu et al., 2021).

Economically, the overgrowth of floating macrophytes incurs substantial costs, ranging from direct expenses for mechanical removal and management to losses in hydropower generation due to turbine and channel blockages. This phenomenon adversely affects crucial economic activities such as tourism and fishing, reducing the attractiveness and accessibility of water bodies. Furthermore, water quality degradation leads to additional costs for Water Treatment Plants (WTPs), increasing expenses for affected municipalities and regions. Mechanical removal of macrophytes can cost millions annually, depending on the frequency and extent of infestations, with indirect costs significantly impacting the local economy (Misteli et al., 2023; Tasker et al., 2022; Yang et al., 2023).

Socially, the excessive proliferation of floating macrophytes affects the lives of riverside communities that depend on the health of aquatic ecosystems for their livelihood, whether through fishing, agriculture, or tourism. Moreover, the excessive presence of these plants can limit access to water resources, complicate water transport, and increase public health risks as stagnant waters can become breeding grounds for vector-borne diseases like malaria (Akowanou et al., 2023).

3.4 Conventional Macrophyte Control Techniques

The physicochemical conditions and nutrient availability in reservoirs are crucial for the survival and development of aquatic macrophytes. High densities of these plants often signal environmental imbalances, such as sewage pollution and the absence of riparian forests. To control excessive macrophyte growth, a specific analysis of each reservoir is essential, considering its dynamics, history, biota, and unique characteristics, to understand how the plants interact with the system (Lu et al., 2018; Manolaki et al., 2020).

In a review study by Karouach et al. (2022), existing approaches to control and manage the proliferation of water hyacinth (*Eichhornia crassipes*) were evaluated, highlighting globally tested control programs. The advantages and disadvantages of the main proposed control methods, including biological, chemical, and physical, were analyzed. The authors suggest that short to medium-term physical control effectively manages plant proliferation, complementing biological control. Moreover, they emphasize that integrated control, combining biological and physical methods, is a more sustainable and economical approach.

While removing macrophytes is necessary to mitigate their negative impacts, the removal techniques, such as mechanical extraction, can disturb aquatic ecosystems and affect local biodiversity. Frequent removal can be costly and labor-intensive, requiring careful management to prevent additional damage to the ecosystem. In some cases, macrophyte removal may have a temporary impact, with vegetation quickly returning if nutrient and water conditions remain favorable (Thiemer et al., 2021).

To control excessive growth of macrophytes, it's crucial to implement integrated management strategies. These include controlling nutrients at the source, such as improving wastewater treatment systems and managing sustainable agricultural practices to reduce nutrient runoff. Additionally, biological methods, like introducing specific herbivorous species, and physical techniques, such as barriers or selective cutting, can be applied to maintain ecological balance and reduce the adverse impacts of macrophytes (Poveda, 2022; Thiemer et al., 2023).

Conventional methods for controlling macrophytes, such as mechanical, chemical, and biological control, each have their pros and cons and are crucial for managing aquatic ecosystems. Mechanical control, despite its immediate efficacy, can negatively impact aquatic biodiversity, affecting organisms such as phytoplankton, zooplankton, and macroinvertebrates. Chemical control, while effective, poses risks of toxicity and environmental contamination. Biological control, considered more sustainable, requires careful management to avoid ecological imbalances (Cerveira Junior et al., 2023; Misteli et al., 2023; Thiemer et al., 2021).

Studies analyzing conventional macrophyte control methods have led to Table 3, which shows that while mechanical and chemical methods offer quicker, direct action, they pose significant sustainability and environmental impact challenges. Conversely, biological control, although potentially more sustainable and with less environmental impact, requires careful evaluation to prevent ecological imbalances. Integrating these methods may provide a more efficient and ecologically responsible solution for managing aquatic macrophytes (Diniz et al., 2005).

Table 3 - Comparative Analysis of Conventional Macrophyte Control Methods.

Control Method	Efficacy	Sustainability	Cost	Environmental Impact
Mechanical	High for immediate removal	Low due to habitat disturbance and need for frequent interventions	High, due to specialized equipment and labor	Potentially high, can disturb aquatic ecosystems
Chemical	High for quick control	Low, risk of toxicity and resistance	Variable, depending on the herbicide	High, risk of contamination and impact on non-target species
Biological	Variable, dependent on the efficacy of the organism	High, more natural and less invasive methods	Initially high, but lower in the long term	Lower, but risk of ecological imbalance if poorly managed

Source: Karouach et al. (2022).

3.5 Fundamentals of Ultrasonic Control

Ultrasonic waves are sound waves with frequencies above the audible limit for humans, that is, above 20,000 Hz (20 kHz). These waves have applications in various fields, from medical diagnostics to industrial cleaning and pest control in aquatic environments. When ultrasonic waves pass through a liquid, such as water in reservoirs, they can induce the phenomenon of acoustic cavitation. This phenomenon occurs when US waves create gas or vapor bubbles in the liquid. These bubbles can grow and collapse rapidly, generating local shock waves and high temperatures. Acoustic cavitation can lead to a series of changes in the cells of aquatic plants. One of the main consequences is microscopic flow, which can alter the internal structure of the cell (Fetyan & Salem Attia, 2020; J. Li et al., 2014; Rajasekhar et al., 2012; Rumyantsev et al., 2021).

The shock waves and mechanical forces generated by the collapse of the bubbles can damage the cell walls of the plants. This damage can be minor, such as small cracks, or severe, leading to the total rupture of the cell wall. Besides the mechanical effects, the energy from the US can be converted into heat, causing thermal effects on the cells. This can alter or damage heat-sensitive cellular components. These combined effects can lead to cell death and tissue damage in aquatic plants. In cases of intense or prolonged exposure to US, generalized plant tissue death may occur, affecting their survival capacity (Dehghani et al., 2023; Kurokawa et al., 2016; B. Ma et al., 2005; Wang et al., 2021).

3.6 Ecological Implications of Ultrasound Use

Ultrasound (US) has been used to control the proliferation of aquatic plants and cyanobacteria in reservoirs and other aquatic environments. While effective in reducing invasive or harmful biomass by damaging the cell walls and tissues of these organisms, it is crucial to assess the intensity and duration of US exposure to protect the aquatic ecosystem, especially non-target organisms (Klemenčič & Klemenčič, 2021; Robles et al., 2022).

3.6.1 Effects of Ultrasonic Control on Non-Target Organisms

Understanding how US affects these organisms is vital to ensure the safety and sustainability of its application. Different species show varying resiliencies to the mechanical effects of acoustic cavitation, which can rupture cell membranes and tissues, implying the need for careful adjustments in the application of ultrasound (Lira et al., 2017; Moftakhari et al., 2022). While some species of fish and invertebrates show minimal or no change, other aquatic life forms, such as certain algae and zooplankton, may experience effects ranging from sublethal to lethal (Anabtawi et al., 2024; Jančula et al., 2014; Lürling & Tolman, 2014).

3.6.2 Long-Term Implications of Ultrasound in Aquatic Ecosystems

Ultrasound shows promising results in controlling algal blooms and macrophyte growth, rapidly reducing biomass. However, its long-term impacts are complex and require a detailed understanding to ensure sustainable applications, especially due to potential effects on aquatic biodiversity (Joyce et al., 2010; Sutherland et al., 2015).

Studies suggest that ultrasound can damage external and internal structures of aquatic organisms, altering their susceptibility to predators and diseases, potentially affecting food chains and the reproduction of key species like zooplankton, algae, and macrophytes, impacting aquatic community structure (Knobloch et al., 2021; Park et al., 2017).

Sonication may release nutrients from lysed cells, such as nitrogen and phosphorus, promoting the growth of microorganisms and potentially intensifying algal blooms after an initial decrease. These effects complicate effective water resource management and require careful strategies (Ghernaout & Elboughdiri, 2020).

Understanding and mitigating the long-term impacts of ultrasound necessitates prolonged studies including detailed ecosystem monitoring. Collaboration across scientific and technical specialties is crucial to develop practices that maximize benefits and minimize environmental risks (Humbert & Quiblier, 2019).

3.6.3 Impacts of Ultrasonic Control on Toxin Release

When cyanobacteria are exposed to ultrasonic radiation, they can release toxins such as microcystins, posing risks to both aquatic life and human health. This is particularly concerning in reservoirs used for water supply and recreation. To mitigate these risks, it is essential to carefully control the application of ultrasonic treatments, monitor water quality continuously, and adapt ultrasound parameters to minimize cyanobacterial stress and toxin release. Further research may enhance the safety and efficacy of ultrasonic methods in managing water environments. (Ghernaout & Elboughdiri, 2020; Peng et al., 2023b; Thodhal Yoganandham & Pei, 2023).

3.6.4 Impacts of Ultrasound on Cyanobacterial Cell Structure and Ecological Consequences

The fragmentation of cyanobacterial cell walls by ultrasound releases substrates that can accelerate microbial biomass, reducing dissolved oxygen and negatively impacting aquatic fauna, potentially causing problems like hypoxia and fish deaths (Wu et al., 2012; Zhan et al., 2021). Contrary to the idea that ultrasonic fragmentation of cyanobacterial cell walls can release toxic substrates and exacerbate hypoxia, research indicates that selecting appropriate ultrasound parameters can avoid complete cellular lysis and consequently the massive release of harmful organic substances. This suggests a potential pathway for environmentally sustainable management of cyanobacterial blooms, using ultrasound to subtly modulate cell viability without causing broad harmful effects to the aquatic ecosystem (Grigoryeva et al., 2018).

3.6.5 Monitoring and Management

Therefore, it can be argued that with precise adjustments and continuous monitoring, the use of ultrasound can be a viable strategy for controlling cyanobacteria populations in an environmentally responsible manner. Implementing rigorous monitoring strategies after ultrasound application is essential. Continuous monitoring of water quality and toxin levels will help ensure that the benefits of control are not undermined by negative environmental impacts (Ali et al., 2020; Burch et al., 2021; Grigoryeva et al., 2018; Rellán et al., 2007).

3.7 Practical Applications of Ultrasound

Ultrasound techniques are used in various fields, such as chemical engineering for dispersing nanoparticles, accelerating chemical reactions, extracting bioactive compounds, and emulsification; in environmental engineering for applications like wastewater treatment, water disinfection, soil remediation, and controlling cyanobacteria and algae, in industrial cleaning, and in separation and extraction processes (Assunção et al., 2022; Cai et al., 2014; Fetyan & Salem Attia, 2020; Kist et al., 2020; Kitamura et al., 2023; Long et al., 2021; Pacheco-Álvarez et al., 2022); in medicine for diagnostics and treatment; in the food industry for processing and preservation (Dolas et al., 2019; Gallo et al., 2018; Song et al., 2021; Zhu et al., 2023). Ultrasound is also applied in the pharmaceutical industry and in nanotechnology for material synthesis. These applications are noted for their efficiency, time and chemical use reduction, and versatility (Lürling & Tolman, 2014; Yücetepe et al., 2019).

These techniques face significant challenges in transitioning from laboratory to industrial settings, notably in terms of measurement precision and reliability. The Ultrasound Laboratory at National Institute of Metrology, Standardization and Industrial Quality (INMETRO) illustrates the complexity of this transition, highlighting the importance of US metrology, transducer and sensor calibration, and metrological characterization of the ultrasonic field. These measures are essential to ensure accuracy in industrial environments, where quality and efficiency standards are stringent (Brasil, 2020; Y. Wang et al., 2022).

Additionally, the energy transition towards more sustainable and energy-efficient processes poses additional challenges, such as integrating renewable sources, modernizing infrastructure, professional training, cultural changes, and political resistance. To meet sustainability goals, companies are adopting strategies like energy reuse, applying the principles of reduce, reuse, and recycle, and efficient asset monitoring. These approaches contribute to both operational efficiency and reducing environmental impact, maintaining the relevance of ultrasonic techniques in engineering research and development (Lampis et al., 2021).

Most modern ultrasonic devices rely on piezoelectric material transducers, which react to small changes in size when an electrical potential is applied. These crystals convert electrical energy into mechanical vibration (sound) at high frequencies, producing ultrasonic sound at sufficiently high alternating potentials. Ultrasonic sound is a form of mechanical energy transmitted by pressure waves in media such as gases, liquids, or solids, with frequencies above the upper limit of human hearing, intensities above 20 kHz (Gallo et al., 2018; Lira et al., 2017).

3.8 Case Studies

The studies by Wu et al. (2011) and Rajasekhar et al. (2012) investigated the use of ultrasound (US) as an effective and environmentally friendly method for controlling cyanobacterial blooms, particularly the species *Microcystis aeruginosa*. It was found that sonication, the application of ultrasonic waves, is effective in controlling these blooms, with efficacy dependent on variables such as frequency, intensity, and exposure time. The results demonstrated that US can effectively inactivate algal cells and has the potential to degrade toxins, offering a promising treatment in pilot scale and field tests. This method, less polluting and feasible for large-scale application, works through the generation of cavitation bubbles that destroy cyanobacterial cells (Purdi et al., 2023).

The study by J. Li et al. (2021) explores the use of ultrasound (US) to control cyanobacterial blooms, focusing on the intracellular structural changes in *Microcystis*. The research assessed the efficiency of cell removal and used transmission electron microscopy (TEM) to visualize structural changes, supplemented by polarized light measurements. It was found that polarization parameters accurately reflect intracellular changes under different sonication durations, correlating with removal efficiency data and TEM images. The study suggests that polarized light is a promising tool to determine the optimal sonication time for effective control of cyanobacterial blooms in the field.

Another study by Xu et al. (2023) also examines the impact of low-frequency ultrasonic treatment on *Microcystis aeruginosa* blooms, showing that while sonication effectively removes algae, it also intensifies the release of organic matter and microcystins. This process accelerates algal decomposition, creates anaerobic conditions, and increases methane production, suggesting that using ultrasound to control algal blooms might increase water toxicity and greenhouse gas emissions.

Peng et al. (2023a) studied how ultrasonic irradiation of extracellular organic matter from algae influences the formation of disinfection byproducts such as trichloromethane and haloacetic acids. The findings indicate that ultrasonic irradiation alters the molecular structure of this matter, increasing the formation of these byproducts due to the activity of free radicals, with significant implications for the safety of treated water.

Another study by V. A. Rumyantsev et al. (2022) explores the effectiveness of low-intensity ultrasound in controlling toxicogenic cyanobacteria like *Synechocystis sp.* in freshwater bodies. The studies show that ultrasonic irradiation causes stress in these cyanobacteria, leading them to thicken their cell walls and produce toxins—a process that consumes a lot of energy and eventually leads to cell death. This method proves promising as an environmentally safe solution to mitigate toxic blooms in water bodies, contributing to the safety of drinking water and environmental protection.

The study by Shi et al. (2023) examines the removal of algae/cyanobacteria and changes in extracellular microcystins during three algae/cyanobacteria inactivation processes using real eutrophic water, evaluating methods like ultrasound (US), copper sulfate, and a biotic algicide (*Bacillus subtilis*). Ultrasound was effective in removing algae/cyanobacteria, but both ultrasound and copper sulfate treatments increased extracellular microcystins. In contrast, the biotic algicide reduced microcystins under certain dosing and reaction time conditions.

In another study, Zhang et al. (2021) address effective removal of cyanobacteria and associated toxins, such as microcystins, using a combination of protozoan grazing and ultrasound treatment. The method disaggregated *Microcystis* colonies, making them more accessible for ingestion by protozoans like Ochromonas, achieving about 80% removal under optimized conditions. This approach not only enhances algae removal efficiency but also minimizes impacts on non-target organisms and contributes to more sustainable management of harmful algal blooms.

Tzanakis et al. (2017) explore the principles and applications of ultrasound focusing on acoustic cavitation in different liquids. Using a 1 kW, 20 kHz piezoelectric transducer, they induced ultrasonic oscillations in deionized water, ethanol, and glycerin, contained in a glass tank. The study focused on the effects of liquid properties on cavitation, including cavitation cloud formation and acoustic emissions, analyzed using a cavitometer. This research is crucial for understanding acoustic cavitation and its implications in various mediums, enhancing knowledge of ultrasound's basic principles and practical applications.

Fetyan and Salem Attia (2020) discuss how ultrasonic waves serve as a novel water treatment technique, acting as an advanced oxidation method to eliminate various contaminants by fundamentally destroying hard-to-degrade organisms and bacterial cells. In another study, Zhang and Xie (2022) examined the bactericidal effects of electrolyzed water and ultrasound on bacteria, finding that their combination could accelerate cell death and minimize early damage to bacteria, offering a more eco-friendly and energy-efficient sterilization technology.

Dehghani et al. (2023) explore the use of sonochemical reactors in water and wastewater purification, highlighting their effectiveness against microbiological hazards that pose environmental and health risks. The review discusses acoustic cavitation reactors, which use ultrasonic energy, and hydrodynamic cavitation reactors, both efficient in deactivating microorganisms, and covers the environmental benefits, energy efficiency, economic aspects, challenges, and potential future research directions of these techniques.

In a study by Wu and Wu (2007), the control of water chestnut (a type of macrophyte) using ultrasound (US) was investigated. This plant is considered an invasive aquatic species. Different frequencies and amplitudes of US, applied directly to the plants via submerged transducers, showed that 20 kHz ultrasound was particularly effective, causing substantial damage to the plant's cells and tissues, resulting in a high mortality rate. Direct application to the stem was more efficient than to the petiole. The study suggests that US is a viable and environmentally safe alternative for managing water chestnut, though further research is needed on impacts on other aquatic species and the implementation of multi-transducer US devices for large-scale use.

In research by Sobral e Santos (2023) a survey was conducted in April 2023 in national and international patent databases—National Institute of Industrial Property (INPI), World Intellectual Property Organization (WIPO), European Patent Office (EPO), and the Lens database—using the terms "macrophytes" AND "ultrasound". Seventy patents were found, of which 12 were selected for critical analysis focusing on the use of US for macrophyte control. These patents vary in methods and devices for applying US in aquatic environments. The authors highlight the potential of US for sustainable control of macrophytes in reservoirs, suggesting the need for more research and the development of new patents in this area.

Research was conducted on the control of aquatic organisms from the perspective of applied methods, efficacy, feasibility, and limitations of US application, and a table of this information was constructed, which can be seen in Table 4.

Table 4 - Studies on the control of aquatic organisms through the application of ultrasound (US).

Study	Method	Efficacy	Viability	Limitations	Reference
A review of the use of sonication to control cyanobacterial blooms	Review of studies that applied sonication with variable frequencies and intensities to inhibit cyanobacteria, focusing on the disruption of gas vacuoles and inhibition of photosynthesis.	Ultrasound proved effective in controlling cyanobacteria, impacting cellular structure, inhibiting photosynthesis, and damaging gas vacuoles. Efficacy depends on factors such as frequency, intensity, and duration of exposure.	The method is considered environmentally friendly compared to other strategies such as the use of algicides.	Sonication can cause the release of toxins such as microcystins from cyanobacterial cells, and selecting appropriate ultrasonic parameters is crucial to avoid this.	(Rajasekhar et al., 2012)
Control of Algal Growth in Reservoirs with Ultrasound	Use of ultrasound at frequencies of 20 kHz and 862 kHz to reduce algal growth, with varying efficacies based on the type of algae.	Greater susceptibility of filamentous cyanobacteria to high-frequency ultrasound. Efficacy varies according to the type of algae.	The study suggests that sonication may not be economically viable as a sole solution for algal blooms due to high energy consumption.	Some species, like *Microcystis* aeruginosa, showed resistance to ultrasound at all tested frequencies.	(Purcell, 2009)
Effect of sonication frequency on the disruption of algae	Investigation of cellular disruption in different algae species using ultrasound frequencies from 0.02 to 4.3 MHz, relating the optimal frequency to the mechanical properties of the cells.	Reduction in the number of algae was dependent on the ultrasound frequency, and different algae species had different optimal frequencies for disruption.	The study suggests that physical effects of ultrasound, such as cavitation, are responsible for disrupting algae.	The need to select the correct frequency for each type of algae can be a challenge in practical application.	(Kurokawa et al., 2016)
Effect of ultrasonic frequency and power on algae suspensions	Study of the impact of ultrasound on *Microcystis aeruginosa* at frequencies from 20 kHz to 1.146 MHz to determine the most effective settings for algae reduction.	The reduction in the number of algae depends on both the frequency and intensity of the ultrasound. Some frequencies were more efficient than others.	The efficiency of ultrasound for algae control is influenced by energy consumption, suggesting that optimal parameter settings are crucial.	The efficacy varied considerably among different frequencies and intensities, indicating the need for careful calibration.	(Joyce et al., 2010)

Source: Authors.

This table provides a comprehensive overview of various research studies examining the effectiveness of ultrasound technology in controlling aquatic organisms, specifically algae and cyanobacteria, under different conditions. Each study focuses on different aspects of ultrasound application, including frequency, intensity, and environmental impact.

3.9 Comparison Between Ultrasonic and Conventional Techniques

Comparing ultrasonic and conventional techniques for controlling aquatic organisms such as cyanobacteria and algae involves assessing various aspects such as efficacy, sustainability, cost-effectiveness, and environmental impacts. Table 5 provides a visual comparison based on these criteria.

Table 5 - Comparison between ultrasonic and conventional techniques for controlling aquatic organisms.

Criteria	Ultrasonic Techniques	Conventional Techniques
Efficacy	- Effective in disrupting and inhibiting cyanobacteria and algae; - Specific to certain types, may require adjustments.	- Generally effective, but may not be specific. - May require multiple applications.
Sustainability	- Environmentally friendly, does not release chemicals. - Low disturbance to the aquatic ecosystem.	- Depending on the technique, may use harmful chemicals. - Can affect aquatic biodiversity.
Cost-effectiveness	- Higher initial cost for installation and calibration. - Low operational costs in the long term.	- Variable costs, depending on the method. - Maintenance and reapplication can be costly.
Environmental Impacts	- Minimalist, mainly due to the absence of chemicals. - May affect species sensitive to ultrasound.	- Potential for chemical pollution. - Risks of ecological imbalance.

Source: Getchell et al. (2022); Klemenčič & Klemenčič (2021); Mullick & Neogi (2017); Svendsen et al. (2018); Tan et al. (2021); Wu & Mason (2017).

This table summarizes the key differences in efficacy, sustainability, cost-effectiveness, and environmental impacts between ultrasonic and conventional techniques for controlling aquatic organisms like cyanobacteria and algae. Ultrasonic techniques are more sustainable and have lower environmental impacts due to the absence of chemicals, making them particularly advantageous in sensitive environments. Conventional techniques, while often effective, can pose greater environmental risks, especially with the use of chemicals. In terms of cost-effectiveness, ultrasonic techniques may be more expensive initially but offer long-term savings due to reduced maintenance and reapplication needs. The choice between techniques should consider the specific context, including the target organism type, ecosystem sensitivity, and available resources.

3.10 Gaps in the Literature and Future Research Directions

Current studies on the control of aquatic organisms, including cyanobacteria, algae, and macrophytes, reveal significant gaps, particularly in the specificity of techniques for different species and in understanding long-term impacts on the aquatic ecosystem. Many studies focus on immediate effects without assessing the recovery of non-target organisms or the development of resistance. Furthermore, there is a lack of comprehensive comparative studies that evaluate the efficacy, cost-effectiveness, and environmental impacts of various control methods, including physical, chemical, biological, and ultrasonic approaches (Huisman et al., 2018; Rocha et al., 2018).

For future research directions, it is essential to explore integrated methods that combine different control techniques, assessing their detailed environmental impacts and developing new technologies for more selective and sustainable control. It is important to study the adaptation and resistance of aquatic organisms to control methods and to consider the socioeconomic aspects, especially for communities dependent on aquatic resources. Developing long-term monitoring and evaluation protocols is also crucial to understand the effectiveness and impacts of control methods (Huisman et al., 2018; Rocha et al., 2018; Zanchett & Oliveira-Filho, 2013).

4. Conclusion

Based on the review of studies on the use of ultrasound (US) for controlling cyanobacteria and macrophytes, it is concluded that frequencies above 20 kHz and, in some cases, higher than 1 MHz are effective in disintegrating cyanobacteria. For macrophytes, the frequency of 20 kHz also showed high efficacy. The recommended exposure time to ultrasonic radiation varies depending on the type of organism and environmental conditions, but studies indicate that exposures of 40 seconds can collapse gas vacuoles that provide buoyancy to these aquatic organisms. Adjustments in intensity and exposure duration are necessary according to specific environmental conditions and the biology of the target organisms to optimize efficacy and avoid significant negative impacts on the aquatic ecosystem. However, most of the studies analyzed were conducted on a laboratory scale.

The observed environmental impacts include the release of toxins, such as microcystins, which can harm both aquatic life and human health. Cellular fragmentation caused by US can lead to hypoxia and fish deaths due to reduced dissolved oxygen, and potentially exacerbate existing ecological problems. These effects underline the need for careful control and continuous monitoring during the application of US to mitigate environmental risks.

The application of US also affects non-target organisms, with different species showing varying degrees of resilience to the effects of acoustic cavitation. While some species may not be significantly affected, others may suffer sublethal or lethal effects, which can impact biodiversity and the dynamics of the aquatic ecosystem. These findings underscore the importance of developing US parameters that minimize damage to non-target organisms.

The long-term effects of using US include possible changes in the aquatic community structure and the susceptibility of organisms to predators and diseases. Additionally, the release of nutrients from lysed cells can promote new algal blooms, complicating effective water resource management. Long-term studies and continuous monitoring are essential to fully understand and mitigate these impacts.

Finally, it is recommended that research continues to develop more efficient and less invasive transducers, as well as interdisciplinary collaboration for testing and applications of this control method on a laboratory scale and on a large scale, such as in reservoirs, in order to optimize the use of US. The integration of adaptive and sustainable control strategies can significantly contribute to efficient and ecological reservoir management, promoting the preservation of biodiversity and the sustainability of water resources.

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