UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CENTRO DE AQUICULTURA DA UNESP

Bioeconomia Aplicada a Sistemas Aquícolas de Produção Integrada de Pescado com Plantas Aquáticas na Associação de Agricultores Familiares no Vale do Ribeira, Brasil

BEATRIZ SOARES HEITZMAN

Jaboticabal, São Paulo

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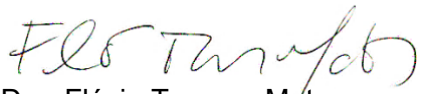
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LISTA DE ABREVIAÇÕES E SIGLAS

Ácidos graxos	Nº de carbono: insaturação
Ácido caproico	C6:0
Ácido caprílico	C8:0
Ácido cáprico	C10:0
Ácido láurico	C12:0
Ácido tridecanoico	C13:0
Ácido mirístico	C14:0
Ácido miristoleico	C14:1
Ácido pentadecanoico	C15:0
Ácido cis-pentadecenoico	C15:1
Ácido palmítico	C16:0
Ácido palmitoleico	C16:1
Ácido heptadecanoico	C17:0
Ácido cis-heptadecenoico	C17:1
Ácido esteárico	C18:0
Ácido n-9c oléico	C18:1
Ácido n-9t elaídico	C18:1
Ácido n-6c linoléico	C18:2
Ácido n-6t linolelaídico	C18:2
Ácido n-3 linolênico	C18:3
Ácido n-6 y linolênico	C18:3
Ácido araquídico	C20:0
Ácido behênico	C22:0
Ácido n-3 cis-eicosatrienoico	C20:3
Ácido n-6 araquidonico	C20:4
Ácido Eicosapentaenoico	C20:5n3
Ácido tricosanoico	C23:0
Ácido Lignocerico	C24:0

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RESUMO GERAL

Os sistemas de produção aquícolas devem adotar métodos e abordagens baseados na economia circular, principalmente ao utilizarem recursos naturais e sistemas biológicos. Este estudo abordou o potencial da *Lemna minor* (lentilha-d'água) como elemento-chave para o fortalecimento da bioeconomia em sistemas de aquicultura familiar, com enfoque na economia circular. Inicialmente, foi realizada uma revisão sistemática de 51 estudos científicos, os quais foram organizados em categorias temáticas: ecotoxicologia, fitorremediação, composição química, bioprodutos e estratégias de cultivo. A análise revelou lacunas relevantes na literatura, sobretudo na integração de dados moleculares, ecológicos e biotecnológicos, essenciais para consolidar o uso da *L. minor* como modelo biológico em práticas sustentáveis. Paralelamente, foi conduzido um experimento em campo com três unidades de produção familiar (UPFs) no Vale do Ribeira, São Paulo, na área do bioma Mata Atlântica, em sistema de aquicultura integrada multitrófica (AIMT), integrando o cultivo de *Clarias gariepinus* com *L. minor* ao longo de doze meses. A macrófita demonstrou alta eficiência na fitorremediação de efluentes aquícolas, promovendo a redução de nutrientes e melhorando a qualidade da água. A biomassa seca obtida apresentou composição rica em proteínas, ácidos graxos, minerais e compostos bioativos, sendo considerada promissora para a produção de rações, alimentos funcionais e nutracêuticos. Por fim, realizamos uma análise bioeconômica avaliando os custos de produção, o retorno econômico e a geração de coprodutos, com vistas ao desenvolvimento de uma tecnologia social replicável para pequenos produtores. Os resultados indicaram que *L. minor* representa uma solução biológica eficiente e acessível, com alto valor agregado, fortalecendo práticas produtivas sustentáveis e inovadoras, alinhadas aos princípios da economia circular e da aquicultura sustentável.

Palavras-Chaves: aquicultura, aquicultura familiar, bioeconomia, economia circular, inovação social, tecnologia social.

GERAL ABSTRACT

Aquaculture production systems must adopt circular-economy-based approaches, especially when using biological systems and natural resources. This study explored the potential of *Lemna minor* (duckweed) as a key component to strengthen the bioeconomy in small-scale aquaculture systems, focusing on circular economy principles. A systematic review of 51 scientific studies was categorized into five thematic areas: ecotoxicology, phytoremediation, chemical composition, bioproducts, and cultivation strategies. The analysis identified notable gaps in the literature, particularly regarding the integration of molecular, ecological, and biotechnological data necessary to establish L. minor as a model organism for sustainable practices. Additionally, a field experiment was conducted in three family-run production units in the Vale do Ribeira region (Atlantic Forest biome, São Paulo, Brazil), implementing an integrated multitrophic aquaculture (IMTA) system that combined *Clarias gariepinus* cultivation with *L. minor* over 12 months. The macrophyte proved highly effective in treating aquaculture effluent, significantly reducing nutrient loads and improving water quality. The harvested dry biomass exhibited a rich composition of proteins, fatty acids, minerals, and bioactive compounds, making it promising for use in feed, functional foods, and nutraceuticals. Finally, a bioeconomic analysis was conducted to assess production costs, economic returns, and co-product generation, with the aim of developing a replicable social technology for smallholders. Results suggest that L. minor offers an efficient, accessible, high-value biological solution that supports sustainable, innovative aquaculture practices aligned with circular economy principles.

Keywords: aquaculture, bioeconomy, circular economy, family farming, social innovation, social technology.

INTRODUÇÃO GERAL

A bioeconomia auxilia na transição dos modelos de produção convencionais e lineares para os mais sustentáveis, ao promover o uso eficiente de recursos biológicos renováveis, como resíduos orgânicos, biomassa e tecnologias limpas. Fundamentada na gestão responsável desses recursos, essa abordagem busca criar novas cadeias de valor capazes de fortalecer a resiliência dos ecossistemas naturais, ao mesmo tempo em que impulsiona a inovação e o desenvolvimento socioeconômico (KARDUNG et al., 2021).

A aquicultura exerce papel central na consolidação da bioeconomia, por ser uma atividade produtiva baseada na exploração racional dos recursos hídricos. No entanto, o setor enfrenta desafios crescentes relacionados a fatores ambientais, econômicos e sociais, que impactam sua sustentabilidade e segurança alimentar (KNOWLE et al., 2020). Uma das alternativas para reduzir os impactos ambientais e tornar estes sistemas produtivos mais sustentáveis, está na implementação de sistemas de aquicultura integrada multitrófica (AIMT) ou similares que empregam a abordagem da economia circular e da bioeconomia (CHOPIN, et al, 2001).

A AIMT consiste no cultivo conjunto de diferentes organismos aquáticos interdependentes no âmbito trófico, como peixes, moluscos, algas e macrófitas aquáticas. Essa integração permite aproveitar resíduos orgânicos e inorgânicos gerados na criação de peixes, convertendo-os em biomassa útil e reduzindo significativamente a carga poluidora dos efluentes (TROELL et al., 2009).

Entre as espécies de peixes mais utilizadas nos sistemas AIMT, o bagre africano (*Clarias gariepinus*) (Figura 1) destaca-se por sua rusticidade, alta resistência a condições ambientais adversas e capacidade de sobrevivência em ambientes com baixos níveis de oxigênio, características que o tornam ideal para unidades produtivas de pequeno porte (HECHT et al., 1988). Segundo a FAO (2020), essa espécie representa cerca de 2,3% da produção aquícola mundial e é amplamente utilizada em projetos voltados à segurança alimentar e ao desenvolvimento de pequenas economias urbanas e periurbanas.

Além dos peixes, as plantas aquáticas também são empregadas nos sistemas AIMT. Dentre diversas opções, a espécie que têm se destacado nas produções integradas é a *Lemna minor* (Figura 2), uma macrófita aquática cosmopolita,

popularmente conhecida por “lentilha d’água” e “*duckweed*”, utilizada em sistema AIMT para reduzir o potencial de impacto ambiental causado pelo efluente no meio aquícola (CERQUEIRA, 2021; FATOBENE et al., 2019; GARCIA, 2015; GRAEFF et al., 2007; MOHEDANO, 2004; PIRES et al., 2003; OLIVEIRA, 2013; TAVARES, 2004).



Figura 1. Juvenil de *Clarias gariepinus* produzidos no sistema AIMT nas Unidades Familiares de Produção (UFPs) no município de Cajati, SP.



Figura 2. *Lemna minor*, popularmente conhecida como “lentilha d’água” e “*duckweed*”. 1) parte inferior, com fronde de 4 mm; 2) *L. minor* com três nervuras visíveis; 3) grupo de duas frondes com cerca de 3 mm, achatadas e com raízes em desenvolvimento; 4) *L. minor* de 4,8 mm cultivado à sombra, com contorno elíptico-alongado; 5) *L. minor* de 4 mm, foto da parte aérea das folhas; 6) *L. minor* de 3 mm, visão das nervuras e espaços aéreos menores. Fonte: Poggiani Luciano.

A biomassa fresca da lentilha d’água produzida em ambientes com alto teor de nitrogênio e fósforo é fonte rica em proteínas, 35 a 43% (APPENROTH et al., 2017), lipídeos, carboidratos, ômega-3 e ômega-6, sendo nutricionalmente adequada para consumo animal e humano. Em países subdesenvolvidos, que utilizam a proteína

animal como fonte de alimento nas comunidades familiares para a subsistência, a biomassa fresca de *L. minor* é destinada principalmente à nutrição de peixes, aves e gado, descartando os custos elevados com rações comerciais (LENG, 1999).

No setor de alimentos à base de plantas para humanos, a biomassa seca é comercializada com alto valor agregado. Uma cepa de alta proteína de lentilha d'água, *Wolffia globosa,* pode oferecer todos os nove aminoácidos essenciais, fibras dietéticas, polifenóis, ferro, zinco e vitamina B_{12} necessários para a alimentação humana e animal (KAPLAN, et al., 2019).

Apesar da utilização tradicional da lentilha-d'água fresca na alimentação humana e animal em países em desenvolvimento (FAO, 2020), a utilização comercial da biomassa seca ainda é limitada, embora produtos experimentais e aplicações em ração animal e biofertilizantes já existam em escala piloto ou regional. Assim, o fomento a tecnologias e processos circulares de produção, integrando animal e vegetal de forma escalonada, deve ser desenvolvido e transferido à sociedade por meio de inovação social. Isto permitirá a exploração de novas áreas de atuação da bioeconomia aplicada à aquicultura, fomentando novas oportunidades ao desenvolver produtos, tecnologias e processos que agregam valor e tornam as pequenas propriedades familiares mais competitivas e sustentáveis ao adotarem a abordagem da economia circular em seus processos de produção.

Este trabalho tem aplicações diretas com os Objetivos do Desenvolvimento Sustentável (ODS) 2030 da Organização das Nações Unidas (ONU): ODS 2 – "Fome Zero e Agricultura Sustentável", ODS 8 – "Trabalho Decente e Crescimento Econômico" e ODS 11 – "Cidades e Comunidades Sustentáveis". A produção de peixes em sistema aquícola integrado multitrófico (AIMT) beneficia comunidades familiares por ser de baixo custo, fácil manejo, e a implantação com a *Lemna minor* promove a biorremediação no efluente, gerando assim coprodutos como fertilizantes e matéria-prima para alimentação humana e animal. Além disso, o sistema proporciona renda extra e representa uma inovação tecnológica, socioeconômica e ambiental, alinhando-se ao perfil de pequenos produtores, com monitoramento e melhorias no processo convencional de piscicultura.

Portanto, a tese foi estruturada em três capítulos. O primeiro consiste em uma revisão sistemática da literatura científica sobre o uso e a aplicação da macrófita *Lemna minor,* a qual será submetida ao periódico *Circular Economy and Sustainability,* da Elsevier. O segundo capítulo apresenta um artigo científico que descreve uma

pesquisa sobre a aplicação de *L. minor* em um sistema de aquicultura integrada multitrófica (AIMT), sob a perspectiva da economia circular, em uma propriedade de agricultura familiar. Esse artigo foi submetido ao periódico *Science of the Total Environment,* da Elsevier. Por fim, o terceiro capítulo apresenta uma pesquisa científica que analisa os aspectos bioeconômicos do sistema AIMT familiar na região da Mata Atlântica e será submetida ao periódico *Aquaculture Economics & Management,* da editora Taylor & Francis.

OBJETIVO GERAL

O objetivo desta tese é investigar o potencial da macrófita *Lemna minor* como instrumento da bioeconomia aplicada à aquicultura familiar, por meio de uma abordagem integrada que compreende: (i) a revisão sistemática da literatura científica sobre seu uso e aplicações sustentáveis; (ii) a avaliação experimental de sua eficiência em sistemas de aquicultura integrada multitrófica (AIMT) em propriedades familiares na região do Vale do Ribeira, sob a ótica da economia circular; e (iii) a análise dos impactos bioeconômicos gerados pela integração de *Lemna minor* e *Clarias gariepinus* em sistemas produtivos em unidades tradicionais instalados no bioma da Mata Atlântica.

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CAPÍTULO I

Advancements in duckweed (*Lemna minor*) research: exploring sustainable applications, bioproducts, and cultivation strategies as potential drivers to circular economy

ABSTRACT

Lemna minor (duckweed) belongs to the family Lemnaceae and is a small, simple, perennial plant commonly found floating or submerged in freshwater environments. The growing interest in using *L. minor* as a biological model for various applications has led to a substantial body of literature covering its potential uses, bioproducts, chemical composition, and cultivation conditions in laboratory settings and open culture systems. However, there is a noticeable gap in current systematic reviews on this species, which makes it difficult to establish a comprehensive database to understand the progress of studies in different fields of this biological model. Fifty-one articles obtained from a systematic search were categorized into predefined groups according to their application: ecotoxicology, phytoremediation, chemical composition/bioproducts, in addition to a section where studies on cultivation strategies were discussed. Some studies that update information on the taxonomic status and morphological characteristics of the species were also explored. This review aims to update, systematically organize and critically evaluate existing knowledge, as well as identify research gaps and highlight promising avenues for future investigations. Highlighting current insights in interdisciplinary areas will enable future researchers to integrate molecular, ecological and biotechnological data, unveiling the great potential of this organism to support circular economy practices and models, through its sustainable applications, innovative bioproducts and cultivation strategies.

Keywords: Aquatic plant, Bioeconomy, Biomass, Circular Economy, Chemical Compounds, Bioprospecting.

1. INTRODUCTION

Duckweed is a small, invasive, free-floating lifestyle aquatic plant. These organisms are globally distributed and have adapted to a wide range of environmental stresses, including every Duckweeds are small, invasive, free-floating aquatic plants that are globally distributed and have adapted to a wide range of environmental stresses, including all classes of contamination (EKPERUSI et al., 2019). Duckweed species are known for being fast-growing, small-flowered plants, meeting all these criteria to be ideal aquatic models for diverse applications (YANG et al., 2023). Duckweeds, belonging to the family Lemnaceae, have attracted attention for their diverse applications in environmental remediation, nutrition, and biotechnology (YANG et al., 2023; ROCCHETTI et al., 2023). Specifically, the genus *Lemna* is composed of 36 species (BOG et al., 2021) and *L. minor is* perhaps the most recognized and widely distributed species within its genus (GERARDO & LIMA, 2022).

Despite being among the smallest in size, it is widely used in research due to its ability to exhibit observable morphological changes visible to the naked eye (VAN HOECK et al., 2015). *L. minor* is characterized by a wide range of phytochemical constituents, including lipids, amino acids, sterols, terpenoids, dipeptides, glucosinolates, phenolic compounds (e.g., gallic acid, tannins, flavonoids), and organic acids (VLADIMIROVA & GEORGIYANTS, 2014; DOGAN et al., 2022; ZHANG et al. 2023; SOSA et al., 2024). Recently, *L. minor* has been considered as a plant-based ingredient for future foods and as an alternative sustainable source of protein (ROCCHETTI et al. 2023). *L. minor* is widely distributed in various freshwater habitats (ALI et al., 2024). This macrophyte provides functions and services to multiple ecosystems (GERARDO et al., 2022); for example, it provides habitat and food for various organisms, including fish and invertebrates. In addition, it helps in water purification by absorbing excess nutrients and pollutants (AHMADI & DURSUN, 2024; GERARDO et al., 2022; TÖRE & ÖZKOÇ, 2020). Additionally, it thrives in nutrient-rich waters and plays a significant role in regulating the pH of aquatic systems (SHARBA et al., 2024).

Regarding its reproduction, it presents both asexual and sexual reproduction. In the asexual mode, it propagates rapidly by budding and vegetative propagation, generating new leaves from the mother plant. Sexual reproduction, which involves the production of flowers and seeds, occurs less frequently. Its life cycle varies between 4

and 5 weeks, and each plant can generate 4 to 12 daughter leaves over this period (LEMON et al., 2001). Recent studies highlight its potential for hybridization, evidencing the formation of new species and greater genetic diversity within the genus (BRAGLIA et al., 2024). This organism has demonstrated a wide range of acceptable growth conditions, both in vivo and in vitro, as reported in the literature (GUPTA & SIL, 2022). Under ideal conditions, it can double its biomass in a few days, being highly adaptable to a wide pH range and showing great tolerance to abiotic factors (CHAKRABARTI et al., 2018; SOSA et al., 2024; SHARBA et al., 2024). Manipulation of environmental parameters, such as salinity, nutrient deprivation, extreme temperatures, light intensity, photoperiod, and the presence of pollutants, such as heavy metals, can impact starch content, foliage coloration, bioactive potential, and protein accumulation (SOWJANYA et al., 2022; VAN DYCK et al., 2021; AKYÜ & ERSUS, 2024; SCHMIDT & GOLDBACH, 2022).

A wide range of applications across various fields has been documented for *L. minor.* In environmental management, it is extensively utilized for phytoremediation, efficiently removing contaminants such as heavy metals, pharmaceuticals, and dyes like methylene blue from wastewater. Additionally, it is widely studied as a model organism in phytotoxicity research (NORI et al., 2025; KITAMURA et al., 2023; IMRON et al., 2021; SABLI et al., 2019; MOUSAVI-KOUHI, 2025). *L. minor* has been frequently used in traditional medicine and homeopathy for many years. It is known to be used externally as an antipyretic, diuretic, anti-inflammatory in upper respiratory tract and chronic rheumatic diseases, as well as in eczema, acne, wound healing, and insect bites (AL-SNAI et al., 2019). Furthermore, it serves as a source of antioxidants with therapeutic potential (DOĞAN et al., 2022; PETROVA-TACHEVA et al., 2020) and has been shown to have potential for the treatment of liver and cognitive impairment, including paracetamol-induced hepatic encephalopathy (SARKAR & KUMAR, 2024).

The *L. minor,* widely consumed in Southeast Asia for decades, is gaining global recognition as a human food. Other species of aquatic duckweed are now marketed in the USA, Europe, Israel, Thailand, and Japan. In the USA, the Food and Drug Administration (FDA) has granted several Generally Recognized as Safe (GRAS) certifications for homeopathic medicines based on *L. minor.* Additionally, a powdered mixture of *Lemna* and *Wolffia* is already being marketed by private companies in the country. This growing interest is driven by its rapid growth and nutritional potential, positioning it as a promising candidate to address global food security challenges.

Although it is emerging as a novel food ingredient, further scientific research is needed to better understand some of its characteristics (SOSA et al., 2024; SHOHAM et al., 2022). Some advances highlight its cultivation in aquaculture as a viable alternative to fish meal, an expensive protein source used in the production of pelleted diets (CHAKRABARTI et al., 2018), while others indicate its potential in innovative fields, such as biodegradable food packaging (LUZI et al., 2022).

In addition, this potential is reinforced by its remarkable productivity under optimal environmental conditions. *L. minor* can achieve a biomass yield of 10–30 tonnes per hectare per year. However, recent data on large-scale production remains limited. For instance, outdoor pilot ponds in Europe have reported estimated productivity ranging from 7 to 22 tonnes of dry weight (DW) per hectare per year (LANDOLT et al., 1986). Furthermore, a semi-commercial IMTA system demonstrated an annual production of over 30 tonnes of protein-rich duckweed biomass (DW) (STEJSKAL et al., 2022). The highest recorded productivity, 68 tonnes per hectare per year, was achieved in Santa Catarina, Brazil, in a pilot study utilizing wastewater lagoons from pig farming (MOHEDANO et al., 2012; DE MATOS et al., 2014).

Furthermore, this model has been studied for its adaptation to local communities as part of their production systems, for example, taking advantage of its capacity for bioremediation of nitrogen compounds in fish farming (HEITZMAN et al., 2024). In a recent study, the aquatic plant was collected from tanks of a floating system on a farm that produced vegetables both hydroponically and in soil, and was later used on site as a biofertilizer for lettuce cultivation. This study highlights how this organism stops being a waste product and becomes a valuable resource within a circular economy model based on biotechnology (BALDI et al., 2024). These studies show the ability to integrate *L. minor* in different applications, such as bioremediation, bioproducts, and strengthening the local economy, aligning with the circular economy principles recently proposed by Papamichael et al. (2024), who highlight three fundamental pillars: (i) Local bioeconomy development, (ii) strengthening and scale up of the bio-based sector and (iii) understanding ecological boundaries of the bioeconomy. Thus, our study aims to highlight each of the biological, ecological and biotechnological characteristics of this plant that make it an ideal and promising model for the creation of innovative businesses, promoting greater circularity, reducing the carbon footprint and providing a sustainable, regenerative raw material integrated into low environmental impact production systems.

Therefore, it is essential to present a well-structured compilation of information on this biological model, with the aim of encouraging research groups to continue their studies and support the development of new projects, aiming to explore the biotechnological potential of *L. minor,* expand its applications in innovative areas and contribute to sustainable solutions in sectors such as food, aquaculture and bioproduction. In this review, we highlight the most relevant studies of recent years and systematically organize the data and results, offering not only a solid basis for advancing research, but also a detailed view of the applications and processes that can be integrated into the concept of circular economy.

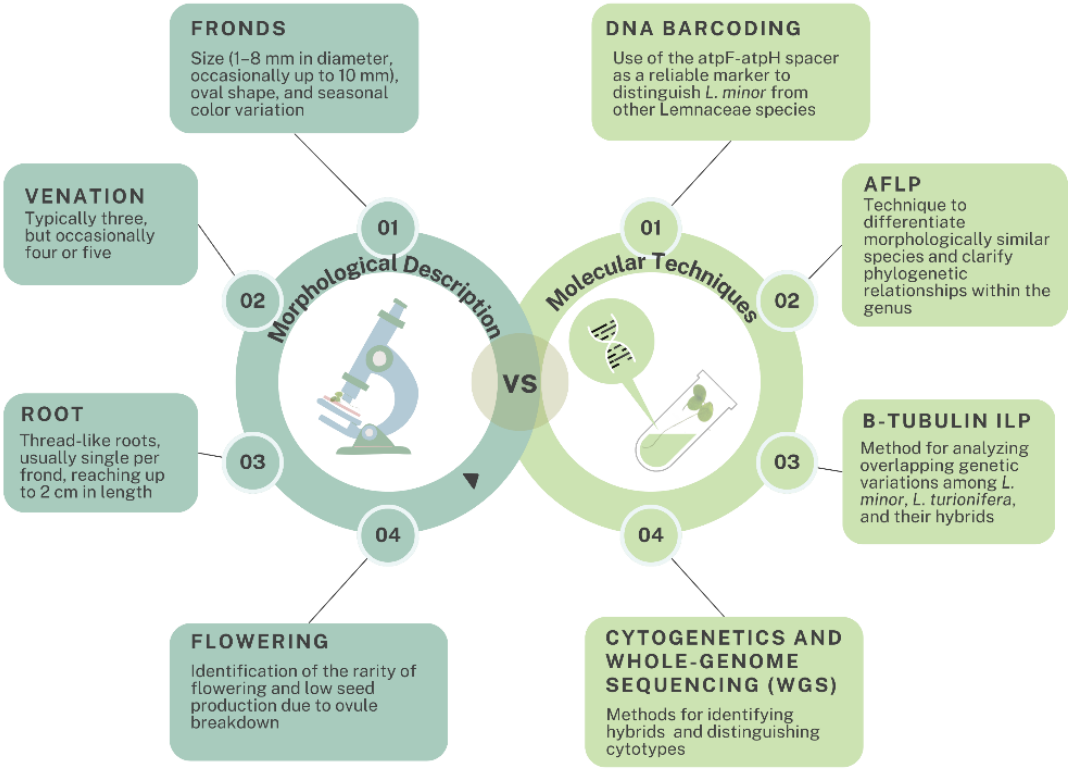


Figure 2. Overview of taxonomic analysis techniques for *L. minor* (1) Morphological Description include frond analysis (size, shape, and color variation), venation observation (vein count), root characterization (length and structure), and records of flowering and fruiting rarity and Molecular techniques for species differentiation involve DNA barcoding (atpF-atpH spacer), AFLP for phylogenetic clarification, β-tubulin intron length polymorphism for hybrid identification, whole-genome sequencing for taxonomic resolution, and cytogenetic.

2. METHODOLOGY

The methodology involved a systematic search for original articles in the Web of Science database, using the descriptors "*L. minor* and products" and "*L. minor* and culture conditions", resulting in 88 and 28 articles, respectively. After applying the publication filter in the period from 2021 to 2024, 35 and 10 articles were selected from these initial searches. Subsequently, an initial reading of the titles and abstracts was carried out to include the articles in pre-defined analysis groups: (1) ecotoxicity, (2) phytoremediation, (3) bioproducts/ chemical composition, and (4) cultivation strategies Additionally, 6 articles were explored descriptively in Google Scholar, using the descriptor "*L. minor* and morphology and taxonomy", with the aim of presenting a detailed approach on taxonomic and morphological aspects of the species. Thus, a total of 51 articles were analyzed in this review.

3. RESULTS

3.1. Taxonomy and morphology L. minor

We address this topic because morphology and taxonomy are crucial for exploring organisms both in the laboratory and economically, because in addition to allowing the classification and identification of species, which is essential for understanding the biodiversity of the places where the species will be studied and explored and the functions that these organisms perform in the ecosystem. In addition, a systematic approach to taxonomy facilitates the development of global databases, increasing the accessibility of information that supports sustainable resource management and informed decision-making regarding the conservation of biodiversity associated with these organisms (SARASWATI et al., 2016). Thus, the accurate characterization of *L. minor* in different regions of the world not only contributes to the expansion of scientific knowledge, but also establishes a solid basis for sustainable practices in areas such as biotechnology and the circular economy. Therefore, the updated information presented here can serve as a valuable resource for researchers to consider in their future applications.

L. minor, commonly known as duckweed, exhibits unique morphological characteristics that complicate its taxonomy. This small, free-floating aquatic plant is primarily identified by its frond, which resembles a leaf and can vary in shape and

pigmentation. Initially described as an aquatic plant from the Lemnaceae family (angiosperms), it has an oval shape and an average diameter of 1.7 mm, forming colonies of at least two to four plants with well-developed root systemsv (SEVERI & FORNASIERO, 1983). Caldwell (1988) provides further detailed inferences on the plant's structure, analyzing the morphology and vegetative multiplication of the sporophyte with protective structures for vegetative buds and flowers. This author describes a plant has a sporophyte with an undifferentiated shoot structure, with differentiation occurring only at the basal and nodal regions, reflecting its adaptation to aquatic environments.

The most recent works that offer morphological descriptions are those of Braglia et al. (2023), who reported that flower formation is infrequent and, when it occurs, the embryo sac structures and ovules usually break, contributing to low seed production. This work highlights hybridization and polyploidization as important drivers of genetic diversity in *L. minor,* complicating species identification because their morphological characteristics overlap with those of other species. On the other hand, Ahmed & Kareem (2024), describe the plant as characterized by its small, green, oval leaves that float on the surface of the water, with a single white central root up to 2 cm tall and one or more green leaves 2–4 mm in diameter, known as leaves (AHMED & KAREEM, 2024).

Regarding taxonomy studies, recent findings of *L. minor* and other duckweed species are advancing and understanding species identification, mainly through molecular techniques, and have been increasingly common, since morphological similarities represent an enormous challenge. Thus, the atpF-atpH spacer was identified as a reliable DNA barcode marker to distinguish *L. minor* from other species of the Lemnaceae family, proving to be effective compared to traditional identification by morphology (WANG et al., 2010). The same atpF-atpH marker was also used to study overlapping genetic variation among *L. minor, L. turionifera* and their hybrid *L japonica*. The study highlights the need for molecular tools, such as β-tubulin intron length polymorphism, to ensure accurate species identification (VOLKOVA et al., 2022).

In 2019, an updated identification key was published for 36 waterfowl species, combining morphological and molecular markers, highlighting the importance of molecular techniques such as DNA barcoding for accurate species identification. *L. minor,* one of the species included in the updated list, details that it is mainly native to

colder oceanic regions of North America, Europe, Africa and western Asia. Its fronds vary from 1 to 8 mm in diameter and 0.6 to 5.0 mm in length, with rare cases of up to 10 mm in diameter and 7 mm in length. The upper surface of *L. minor* is shiny, with a rare yellowish hue in cold seasons, and normally presents 3 nerves, occasionally 4 to 5. Flowering and fruiting are rarely frequent, as the ovaries contain a single ovule (BOG et al., 2019).

The same research group reviewed molecular taxonomy in five genera, emphasizing the need for more genetic analyses, including complete genome sequencing, to resolve taxonomic uncertainties, such as the classification of *L minor* that remaining obscure due to overlapping characteristics with species such as *L. minuta* and *L. valdiviana*. To address these challenges, molecular methods such as AFLP and barcoding are used to distinguish *L. minor* from other species, but this study suggests that further genetic analyzes are necessary to clarify the relationships within the genus (BOG et al., 2020). On the other hand, the studies collectively highlight the growing role of molecular taxonomy in solving two taxonomic challenges, in the case of Braglia et al. (2023), where they discovered *Lemna* × mediterranea, is a hybrid between *L. minor* and *L. gibba*, and revealing different cytotypes, thereby clarifying the phylogenetic position of *L. minor* despite the morphological overlap with hybrids (BRAGLIA et al., 2023).

The taxonomy of *L. minor is* complex due to its morphological plasticity and frequent hybridization with closely related species. While traditional identification methods rely on frond structure and pigmentation, molecular techniques such as DNA barcoding and AFLP analysis have proven essential for distinguishing taxa. Some recent findings highlight the role of hybridization and polyploidy in shaping genetic diversity within the Lemnaceae family. The integration of whole-genome sequencing and β-tubulin intron length polymorphism analysis is expected to further refine taxonomic classifications. Current research continues to fill gaps in species identification, emphasizing the need for more modern molecular approaches.

3.2. Currently Applications

Among the applications identified in the review, a predominance of studies was observed that use *L. minor as* a biological model to assess the toxicity of different substances. Next, research focused on its application in phytoremediation stands out, as well as investigations into its chemical composition and potential for obtaining bioproducts. In this last group, strategic sectors stand out, such as the food industry, biogas production and the development of nanomaterials. Each of these approaches will be analyzed in detail in the following sections, with the presentation and discussion of the main data relevant to bioprospecting in these areas (Figure 3A-B).

Studies have been led by countries that individually account for approximately 8.7% of all studies using *L. minor.* Among them, Poland, the United States, Iran, Turkey and Germany stand out, focusing on research in areas such as ecotoxicity and phytoremediation. Other countries, such as Greece, India, Canada, China, Malaysia, Italy and Russia, each account for approximately 6.5%, while nations such as Ecuador, South Korea, the Czech Republic, Slovenia, Slovakia, Hungary, Ukraine, Egypt, Brazil, Bulgaria, Romania and Japan, among others, appear with unique occurrences. These data highlight the broad and diverse global interest in research and application of the model (Figure 3C). It is important to highlight that in our systematic search, within these studies, two Latin American countries stand out as significant scientific contributions, highlighting the relevance of encouraging more research in Latin American nations using this biological model.

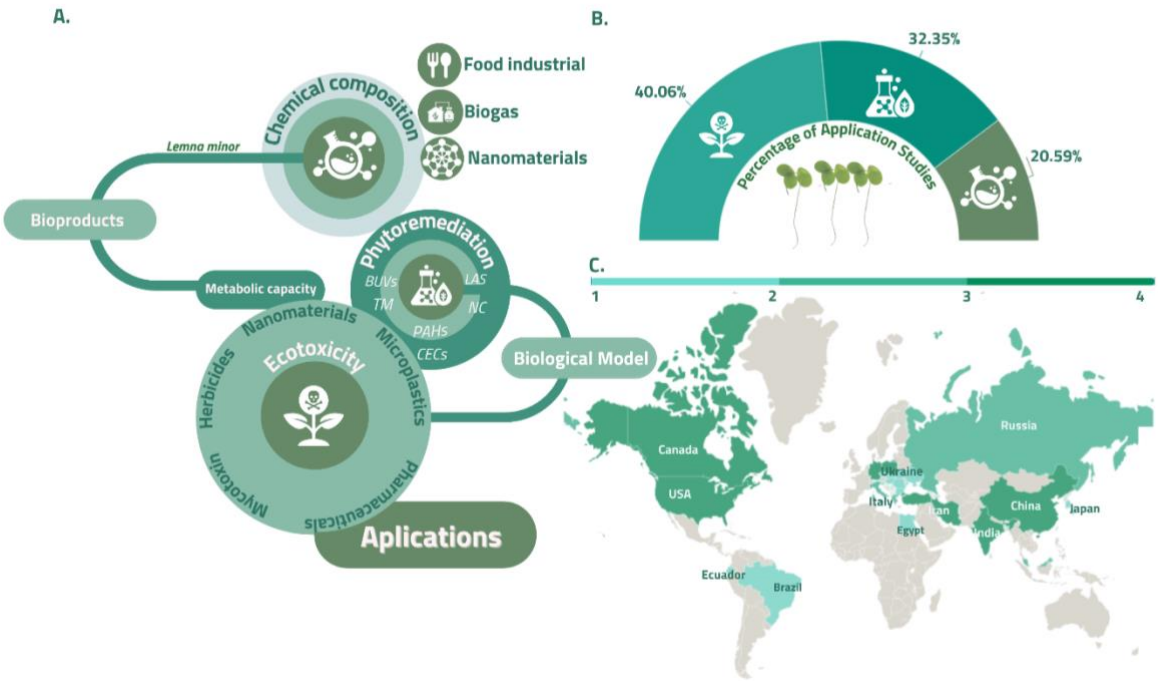


Figure 3. Current applications of *L. minor* . (A) Diagram illustrating three main application areas identified in the systematic literature review: (i) Ecotoxicological bioassays, to test nanomaterials, herbicides, microplastics, mycotoxins and other contaminants; (ii) Phytoremediation, highlighting its ability to remove pollutants such as benzotriazole-based UV filters (BUVs), toxic heavy metals (TMs), nitrogen compounds (NCs), alkylbenzene sulfonates (LAS), polycyclic aromatic hydrocarbons (PAHs) and emerging contaminants (CECs); and (iii) Bioproduct, exploring its chemical composition and feasibility for industrial applications, including food industry, biomaterials, bioenergy and biostimulants. (B) Graph showing the proportion of each application among the studies reviewed. (C) Global distribution map of studies using *L. minor* analyzed in this review.

3.3. Ecotoxicity and L. minor

Human activities contribute to soil and water pollution by introducing a wide variety of contaminants into natural ecosystems, such as pesticides, pharmaceuticals, plastics, endocrine disruptors, antibiotics and other emerging pollutants, which pose significant risks to environmental health and biodiversity. Biological models, such as *L. minor,* have proven to be of interest in toxicity studies due to their sensitivity and ability to reflect the impacts of these pollutants on aquatic systems. These models allow the assessment of the direct effects of pollutants and the impacts of their degradation products. The studies reviewed use *L. minor* as a model organism to assess the toxicity of various substances, including microplastics (CUI et al., 2023; KLUNE et al., 2022), pesticides or herbicide (LI et al., 2022; WEMBE et al., 2023; HERRERA et al., 2023), pharmaceuticals (ZEZULKA et al., 2023; SURESH & ABRAHAM, 2023), nanoparticles (TRAN et al., 2023; FU et al., 2023), mycotoxins (LI et al., 2022; OLADELE et al., 2024), and others Chemical compounds. Growth parameters (frond number, biomass, frond area), photosynthetic health (chlorophyll content, fluorescence), stress mechanisms (antioxidant enzymes), and metabolomic analyses are often used to assess toxicity in *L. minor*. Exposure times vary, but many studies use a 7-day period to assess medium-term effects (Table 1).

Table 1. *L. minor as* a model organism to assess the toxicity of various substances, including microplastics, pesticides, pharmaceuticals, metals, nanoparticles, mycotoxins, and other pollutants.

Category	Compounds evaluated	Main Findings (toxicity measures)	Parameters tested	Author
Nanomaterial	Silver Nanoparticles (AgNPs) and Silver nitrate (AgNO3)	500 µg/L AgNPs: 12% inhibition of frond number; 30% inhibition of leaf area 1000 µg/L AgNPs: 38% inhibition of frond number; 75% inhibition of leaf area.	Frond number, Dry weight, and Frond area.	Tran et al., 2023
Nanomaterial	Core-shell Au@Nanoplastics (Au@NPs)	Inhibition ate of fresh weight in 0.1, 1, and 10 mg/L: 20-30%	Inhibition Rate	FU et al., 2023
Herbicide	Rracemic imazamox (Rac-IM), R-imazamox (R-IM), and S-imazamox (S-IM)	EC 50: Rac-imazamox: 0,036 mg/L R-imazamox: 0,035 mg/L S-imazamox: 0,203 mg/L	Content of photosynthetic pigments (chl a, chl b. Car); Protein content; MDA Content; Activity of antioxidant enzymes (glutathione, CAT, POD, SOD); Activity of ALS	LI et al., 2022
Herbicide	Atrazine (ATR), bis-Phenol A (BPA), Diazinon (DAZ), and Diclofenac sodium (DCF)	DCF-Fe(II)Mt, DCF-HMt-1 and BPA-HMt-1 mixtures, the ChlA/ChlB ratio dropped to zero after 10 min of ozonation; Ozonated DCF mixture: Maximum increase in biomass; BPA mixture: Sharp decrease in biomass with increased ozonation.	Total chlorophyll content (ChlT); Chl a/ Chl b ratio; Protein Content; Biomass Measurement; pH Levels	Wembe et al., 2023
Fungicide	Difenoconazole and atrazine	LC50-48h for difenoconazole is 0.97 mg/L; LC50-48h for atrazine is 86.19 mg/L.	Number of leaves; Biomass; Chlorophyll content (chl-a and chll-b)	Herrera et al., 2023
Microplastics	Polyethylene terephthalate (PET) fragments	% Photosynthetic activity (0–200 µm): 135 %; Color table representing the toxic effects (multigenerational test); PET 0-200 mm exhibited greater toxicity compared to larger fragments;	Number of fronds, frond area and root length. Root cell viability. Effects on photosynthesis with F0, Fm, Fv/Fm, ΦPSII, NPQ , qN, qP and qL. Chloroplast distribution	Cui et al., 2023

Microplastics	Bakelite microplastics and their leachates	Growth: No significant effect (inhibition: 0%). Roots: Significant inhibition before leaching (42%) and with leachates (31%); minimal after leaching (6%). Chlorophyll: No significant changes (inhibition: 0%	Chlorophyll a and b content Specific growth rate Root length Adhesion of microplastics to roots and fronds	Klune et al., 2022
Pharmaceuticals	Naproxen sodium salt (NPX) and paracetamol (PCT), both of which are non-steroidal anti-inflammatory drugs (NSAIDs).	Photosynthetic pigment reduction: 30% decrease at 10 mg/L for both drugs. Hill reaction inhibition: >10% decline across 0.1–10 mg/L treatments. NPX bioaccumulation: 43.22 µg/g DW at 10 mg/L (BCF: high). PCT bioaccumulation: 275.88 µg/g DW at 10 mg/L (BCF: 27.6). Growth inhibition: NPX reduced new plants by 9% (1 mg/L) and 26% (10 mg/L)	Growth and photosynthetic processes; Number of plants per well; Dry weight (mg per plant) Leaf area (mm² per plant)	Zezulka et al., 2023
Pharmaceuticals and hormones	Acetaminophen, diclofenac, ibuprofen, testosterone, progesterone, and estrogen).	Toxicity index range: 2.5 - 3.3 (acetaminophen, diclofenac, ibuprofen, testosterone, progesterone and estrogen); Toxicity index range: 1.1 - 1.5 (Degraded Compounds)	Frond Biomass; Total Pigment Content Toxicity Index; New Frond Formation Specific Chlorophyll Absorbance	Suresh & Abraham, 2023
Mycotoxins	Deoxynivalenol (DON)	DON induced reductions of 6%, 11%, 16%, 33% and 55% in the growth rate of L. minor when exposed to 0.1, 0.5, 1, 2 and 5 ppm DON, respectively.	Number of fronds; Surface area, Chlorophyll content; Growth rate; Percentage inhibition	Oladele et al., 2024
Mycotoxins	Deoxynivalenol (DON), 3-keto-DON, and 3-epi-DON.	IC50: DON: 0,80 ± 0,14 µg/mL 3-ceto-DON: 0,35 ± 0,12 µg/mL 3-epi-DON: 34,04 ± 6,55 µg/mL	Inhibition Growth Fronds Coleoptile Length Fresh Weight of Coleoptiles Fresh Weight of Roots	LI et al., 2022

Others chemical compounds (ultraviolet (UV) filter)	Oxybenzone (OBZ)	IC50 value: Growth inhibition (number of fronds): 8.53 mg/L Chlorophyll a: 7.47 mg/L Chlorophyll b: 9.96 mg/L Total chlorophyll: 8.23 mg/L Carotenoids: 13.12 mg/L Protein: 4.89 mg/L CAT (catalase): 4.34 mg/L POD (peroxidase): 5.74 mg/L	Growth rate; Doubling time; Growth inhibition. Content of photosynthetic pigments (chlorophyll a, chlorophyll b, carotenoids).; Protein content; Activity of antioxidant enzymes (catalase and guaiacol peroxidase)	Sawant et al., 2024
Others Chemical compounds	Surfactants	Wastewater treatment plants, root based (WWTPs) preliminary ecotoxicity tests: negative results; Surfactant Content (mg/L): 3.62, 2.74, 2.74 (positive results)	Growth inhibition	Lobotková et al., 2022
Others Chemical compounds (Waste industrial)	Waste from TiO2 production (LAW, UFP, NFP, NFR; SR.	EC20 (Minimal dilution to reach max 20% inhibition): LAW: 100,000; UFP: 1,000; NFP: 100; NFR: 100; SR: <100 EC50 (Minimal dilution to reach max 50% inhibition): LAW: 10,000; UFP: 1,000; NFP: <100; NFR: 100; SR: <100	Content of photosynthetic pigments; Frond Number	Ildikó Fekete-Kertész et al., 2024
Biological compounds	Lipopeptides (LP) extracted from the olive tree endophyte Bacillus sp. PTA13	The EC25 (concentration causing 25% inhibition) was 156 µg mL−1 based on chlorophyll α content. The EC50 (concentration causing 50% inhibition) was 419 µg mL−1 based on chlorophyll α content	The number of fronds, and the contents of chlorophyll and carotenoids	Papadopoulou et al., 2022
Others Chemical compounds (poly- and perfluoroalkyl substances (PFAS)	PFOA; PFOS; HFPO-DA, GenX (PFBS)	leachates from PFAS-spiked soil (0.1 mg/mL) resulted in a 76% decrease in frond number, a 36% decrease in surface area, and a 78% reduction in chlorophyll content after 7 days of exposure	Frond number; surface area, chlorophyll content	Wang et al., 2024

Abbreviations and acronyms: Measurements taken include F_0 (minimum fluorescence), Fm (maximum fluorescence), Fv/Fm (maximum quantum yield of PSII), ΦPSII (effective quantum yield of PSII), NPQ

(non-photochemical quenching), qN (non-photochemical quenching coefficient), qP (photochemical quenching coefficient), and qL (quantum yield of PSII under light stress). Naturally Occurring Radioactive Matter (NORM), and various perfluorinated compounds such as PFOA (perfluorooctanoic acid), PFOS (perfluorooctanesulfonic acid), HFPO-DA (hexafluoropropylene oxide dimer acid, GenX), and PFBS (perfluorobutane sulfonic acid). Abbreviations used in the table include Chl (chlorophyll), Car (carotenoid), MDA (malondialdehyde), ALS (acetolactate synthase), DCF-Fe (II)Mt (diclofenac interacting with iron (II) montmorillonite), DCF-HMt-1 (diclofenac interacting with hectorite montmorillonite), and BPA-HMt-1 (bisphenol A interacting with hectorite montmorillonite). Waste types are LAW (Liquid Acid Waste), UFP (Ultrafiltration Permeate), NFP (Nanofiltration Permeate), NFR (Nanofiltration Retentate), and SR (Solid Waste). Concentration effectiveness is measured by EC20 (effective concentration for 20% inhibition) and EC50 (effective concentration for 50% inhibition).

Nanomaterials: There is currently a growing interest in research on the toxicity of nanomaterials, which highlights the need for a comprehensive assessment considering factors such as size, surface charge, material type, exposure time, and toxicity mechanisms. The use of *L. minor* as a model offers valuable tools to understand and mitigate the environmental risks associated with nanomaterials. Such as silver nanoparticles (AgNPs), which are popular nanomaterials in consumer products due to their antibacterial properties and multifunctional applications, in aquatic ecosystems, but they pose threats to ecosystem processes and aquatic organisms (Lee et al. 2012). Tran et al. (2023) investigated how the toxicity of silver nanoparticles (AgNPs) and silver nitrate (AgNO3) on *L. minor* varies at different initial plant densities. Both AgNPs and AgNO3 inhibited the growth of *L. minor,* with more pronounced toxic effects at high plant densities (40 and 80 leaves per area), concluding that at higher densities, competition for resources and space exacerbated the toxic effects of silver.

On the other hand, the main objective of the study by Fu et al. (2023) was to develop a simple and reliable method to study the fate and behavior of nanoparticles (NPs) in freshwater ecosystems, using core-shell gold (Au) nanoparticles as tracers, evaluating the toxic effects of these nanoparticles on *L. minor.* The results showed that both positively and negatively charged Au@NPs significantly inhibited the growth of the model organism and negatively charged Au@NPs were more easily internalized. They concluded that the Au@NPs core-shell tracer model can be used simply and effectively to study the environmental fate and behavior of NPs in complex environmental systems.

Herbicide and pesticide: High concentrations of pesticide residues in soil contribute to the pollution of aquatic ecosystems through processes such as runoff and leaching (CHIAIA-HERNANDEZ et al., 2017). *L. minor,* due to its sensitivity to

pollutants, has stood out for years as an ideal model species to evaluate phytotoxicity and environmental risks associated with the use of pesticides (LI et al., 2022). The use of clays as adsorbents and catalysts in the ozonation of organic pollutants, such as atrazine, bisphenol A, diazinon, and sodium diclofenac, was investigated to simulate their natural degradation in clayey soils. Furthermore, the ecotoxicity of partially oxidized mixtures was evaluated in *L. minor,* demonstrating that toxicity is influenced by changes in pH and the molecular structure of the compounds (WEMBE et al., 2023). Another study determined the enantioselective toxicity mechanisms of the chiral pesticide imazamox (IM) using metabolomic and transcriptomic tools, revealing that R-IM and Rac-IM present greater toxicity compared to S-IM, inducing oxidative stress, lipid peroxidation and alterations in metabolic pathways related to photosynthesis and antioxidant responses in the model (LI et al., 2022). Additionally, the toxicity of difenoconazole and atrazine, as well as their photodegradation products, was analyzed, showing impacts such as reduction in biomass and chlorophyll content, in addition to mortality in *L. minor,* even after degradation (HERRERA et al., 2023).

Microplastics (MPs): The large-scale production and improper disposal of plastics have led to widespread environmental contamination by microplastics (MPs), which pose significant ecological risks. In aquatic ecosystems, MPs induce mechanical stress following ingestion and adsorption, as well as chemical stress due to leachates and associated contaminants (JAMBECK et al., 2015; SCHRANK et al., 2019). In this context, advances have been made in the use of *L. minor* as a model organism to evaluate these impacts. Recent studies illustrate these advances. Cui et al. (2023) demonstrated that PET MPs in different sizes negatively impact *L. minor,* with smaller fragments (0-200 μm) affecting photosynthesis more and larger fragments (300-500 μm) inhibiting growth over 10 generations, in addition to disturbances in chloroplast distribution and reduction in photosynthetic activity. Klune et al. (2022) evaluated Bakelite MPs and their leachates affecting the root length of *L. minor,* without altering their growth rates or chlorophyll.

Pharmaceuticals: These compounds enter aquatic environments mainly through wastewater, often persisting due to inefficient treatment. Their continuous release often exceeds degradation rates, leading to pseudo-persistence in surface waters and classification as contaminants of emerging concern (CEC), and their fate

and potential impacts on non-target organisms, such as plants, are only poorly understood (O'FLYNN et al., 2021; ZEZULKA et al., 2023). highlighting the need for further research on the use of *L. minor* as a model to assess the toxicity of these compounds and its potential as a bioindicator in aquatic ecosystems. In this aspect, Zezulka et al. (2023) evaluated the toxicity of the anti-inflammatory drugs naproxen (NPX) and paracetamol (PCT) in *L. minor* over 7 days. The plant absorbed more PCT, but only NPX reduced reproduction, increasing biomass and leaf area. Both drugs decreased photosynthetic pigments (~30% at 10 mg/L), with NPX affecting photosynthetic efficiency by up to 10% (ZEZULKA et al., 2023). On the other hand, Suresh & Abraham (2023) evaluated the ability of the fungus *Penicillium aurantiogriseum* 2AJS to degrade paracetamol, diclofenac, ibuprofen, estrogen, progesterone, and testosterone, reaching up to 95.27% paracetamol removal. Tests with *L. minor* indicated low phytotoxicity, with no impact on photosynthetic pigments and an increase in the number of fronds, but the degraded compounds showed lower toxicity (index 1.1–1.5) compared to the originals (2.5–3.3).

Mycotoxins: Contamination of agricultural products by toxins is increasing, especially in cereals and grains, due to climate change. To develop effective methods for the biodetoxification of deoxynivalenol (DON), it is essential to evaluate its stability and non-processability and toxicity of its metabolites (LANA et al., 2021; HASSAN et al., 2015). This will allow safe and efficient industrial applications. Some studies have evaluated the toxicological effects of deoxynivalenol (DON) (LI et al., 2022; OLDELE et al., 2024). Among the most important findings, they highlight that 3-keto-DON maintains high toxicity, while 3-epi-DON presents reduced toxicity. Furthermore, exposure to DON reduced growth by 55%. Demonstrating that DON metabolites can have different toxicological profiles and highlighting the importance of evaluating their environmental impacts in multiple biological models.

Others Chemical and biological compounds: Recent studies have explored the effects of surfactants, oxybenzone (OBZ), and biological extracts on *L. minor,* providing valuable insights into the potential risks posed by these substances. Three papers addressing these compounds are detailed below. Sawant et al. (2024) evaluated the acute toxicity of oxybenzone (OBZ) on *L. minor,* revealing significant growth inhibition at higher concentrations. The IC50 was determined to be 8.53 mg/L,

with a hormesis effect observed at lower concentrations. Exposure to OBZ led to a reduction in photosynthetic pigments and an absence of protein content, indicating metabolic disturbances. Lobotková et al. (2022) examined the efficiency of root-based wastewater treatment plants (root-based WWTPs) in surfactant removal, but the main objective of ecotoxicological tests using *L. minor* was to evaluate the impact of contaminants, especially heavy metals and complex residues, on chlorophyll content and frond number to assess plant health in contaminated environments. The results of this research aim to contribute to the development of standardized ecotoxicity assessment protocols and improving the classification of this type of residues (FEKETE-KERTÉSZ et al., 2024). It is also important to highlight that compound of biological origin can be monitored using the *L. minor* model. For example, Papadopoulou et al. (2022) investigated the toxicity of lipopeptides (LP) extracted from the endophyte Bacillus sp. PTA13, finding EC25 (156 ppm) and EC50 (419 ppm) values based on chlorophyll content. The LP extract showed low phytotoxicity, with non-model phenotypic changes such as mild chlorosis and apical discoloration at higher concentrations.

In summary, these studies highlight the ongoing and critical role of *L. minor* as a versatile model organism to assess the ecotoxicological effects of diverse contaminants. Current findings reveal that different pollutants, based on their unique physicochemical properties and exposure conditions, induce diverse toxic responses, such as growth inhibition, photosynthetic impairment, and metabolic disturbances. These diverse results highlight the need to motivate the development of standardized ecotoxicity assessment protocols to improve the classification of environmental risks, guide remediation strategies, and ultimately protect aquatic life from emerging contaminants.

The integration of ecotoxicity models represents a promising path for sustainable innovation. Species such as *L. minor* can be used in biosensors for environmental monitoring, creating effective warning systems for pollutants and enabling the development of new ecotechnological products (NEAGU et al., 2014). On the other hand, studies such as that of Azizullah et al. (2018), which evaluated the ecotoxicity of anti-dandruff shampoos, demonstrate the relevance of these models for the cosmetics industry, where they can offer a sustainable alternative for the initial screening of compounds, reducing the need for conventional tests on animal cells. In addition to adding value to the use of this ecotoxicity model, this approach also allows

the exploitation of the waste generated in these processes to create new bioproducts, strengthening sustainable practices and promoting a closed cycle of innovation and reuse of resources (YALCIN, 2021).

3.4. Phytoremediation and L. minor

Several studies have explored the potential of *L. minor* for the bioremediation of pollutants in water, highlighting its applicability in different scenarios (Table 2) Several studies have explored its potential for the bioremediation of pollutants in water, highlighting its applicability in different scenarios. This table summarizes the studies classified for this application, which evaluated the removal efficiency of different contaminants, including CECs, antibiotics, heavy metals, surfactants, PAHs, pharmaceuticals, and nitrogen compounds, when treated with *L. minor plants*. The summarized data, reported by several studies, highlight reductions ranging from modest decreases to near-complete removals, highlighting the current potential of this aquatic plant as a bioremediation model to mitigate environmental pollution.

Table 2. Representative studies on *L. minor* for phytoremediation of environmental contaminants.

Compound /contaminant	Class	Concentration after treatment	Author
BPA, TRC, E1, E2	CECs	Removal efficiency: Bisphenol A (BPA): between 19% and 70% (1 days); Triclosan (TRC): 84-93% (6 days); Estrone (E1) and Estradiol (E2): over 95% (7 days)	Kotowska et al., 2024
LAS	Anionic surfactants	Bioremoval efficiency: Approximately 60% after 7 days of treatment with an initial concentration of 20 mg/L.	Masoudia et al., 2022
PYR and PHE	PAHs	PHE: 10 mg L^-1 to 0,03 mg g^-1 de peso fresco (FW); PYR: 10 mg L^-1 to 1.237 mg g^-1 FW	Zazouli et al., 2022
Suspended pollutants, oil products, biogenic substances: NO_3, $^{-}NH_4^{+}$, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}	Various	COD: Reduced by 89.6% (from 54.20 mgO_2/dm^3 to 5.62 mgO_2/dm^3); BOD: Decreased by 61.2% (from 14.50 mgO_2/dm^3 to 5.62 mgO_2/dm^3); Oil Products: Dropped by 30%, reaching 1.4× the TLV; Phosphate: Decreased by 83.3% (from 12.6 mg/dm^3 to 2.1 mg/dm^3); Ammonium Nitrogen: Reduced by 75.8% (from 1.90 mg/dm^3 to 0.46 mg/dm^3); Toxic Salts: Treatment efficiency reached 97.7%	Pichura et al., 2022
CIP	Fluoroquinolone class antibiotic	CI: Removal efficiency: 100% Specific conditions: 25 mg/L concentration, pH 3, and 0.75 g/L dosage	Murat Yilmaz et al., 2024

BTAH and its transformation products	TAZ	Benzotriazole degradation: 0.30–0.37% due to transformation products.	O'Brien et al., 2022
UV-P; UV-326; UV-327; UV-328; UV-320	Benzotriazole UV filters (BUVs)	97% removal rate for UV-326 and 100% for UV-327 after 14 days of cultivation	Polińska et al., 2024
Cd	Toxic heavy metal	HCD strain Cd uptake: 238.06 mg/kg (DW) in 24h; LCD strain Cd uptake: 127.63 mg/kg (DW) in 7 days; HCD bioconcentration factor (BCF): Peak of 640.45 in 24h.	Yang et al., 2023
NH_4^+, NO_3^-, PO_4^{3-}	Nitrogen compounds	In system II, Removal (6 days) NH_4^+: 100%; NO_3^-: 93.15% PO_4^{3-}: 87.81%	Heitzman et al., 2024
Industrial and municipal wastewater (BOD, COD, and TC)	Biological Indicators	Fecal coliforms: 100% reduction (municipal and industrial treatments) BOD (Municipal treatment with aeration): Day 5: 56.67 mg O_2/L Day 10: 43.33 mg O_2/L Day 15: 30.00 mg O_2/L BOD (Industrial treatment without aeration): 40.00 mg O_2/L (Day 15) COD (Industrial treatment without aeration): 87.8 mg O_2/L	Abadi et al., 2021
NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}	Nitrogen compounds	Removal efficiency: NH_4^+-: 85.40%; NO3-(16.96%); NO_2^--N (14.20% to 4.73%); PO4-3 (9.09%)	Tekogul et al., 2023

Abbreviations and acronyms: UV stabilizers: 2-(2-hydroxy-5-methylphenyl) benzotriazole (UV-P), 2-tert-butyl-6-(5-chloro-2H-benzotriazol-2-yl)-4-methylphenol (UV-326), 2,4-di-tert-butyl-6-(5-chloro-2H-benzotriazol-2-yl) phenol (UV-327), 2-(2H-benzotriazol-2-yl)-4,6-di-tert-pentylphenol (UV-328), 2-(2H-benzotriazol-2-yl)-4-(1,1,3,3-tetramethylbutyl)phenol (UV-320). Contaminants of emerging concern (CECs): Bisphenol A (BPA), Triclosan (TRC), Estrone (E1), Estradiol (E2), Ciprofloxacin (CIP), Benzotriazole (BTAH). Polycyclic aromatic hydrocarbons (PAHs): Phenanthrene (PHE), Pyrene (PYR). Surfactants: Alkylbenzene sulfonate (LAS). Heavy metals and industrial pollutants: Cadmium (Cd), Triazole compounds (TAZ). Nutrients and ions: Nitrate (NO_3^-), Ammonium nitrogen (NH_4^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^+) and Potassium (K^+), Phosphate (PO_4^{3-}). Water quality indicators: Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), TC: Total Coliforms.

Zazouli et al. (2022) investigated the plant's ability to remediate polycyclic aromatic hydrocarbons (PAHs), such as phenanthrene and pyrene, while Yang et al. (2023) analyzed the effects of cadmium (Cd) on two *L. minor* strains, focusing on growth, Cd accumulation, and antioxidant enzyme activity. Furthermore, *L. minor* has shown its effectiveness in removing benzotriazole UV filters (BUVs) from polluted waters (MURAT YILMAZ et al., 2024). On the other hand, the bioremediation capacity of linear alkylbenzene sulfonate (LAS) has been evaluated, showing that factors such as concentration, temperature and pH influence the removal efficiency (MASOUDIA et al., 2022a). Furthermore, this model has been shown to help clean water on small fish farms using their natural abilities, focusing on improving water quality and creating

useful products from their growth in the Brazilian Atlantic Forest (HEITZMAN et al., 2024). Conversely, studies have registred how *L. minor* reduces BOD and COD levels, as well as the number fecal coliforms, in the treatment of industrial and municipal effluents (ABADI et al., 2021). Tekogul et al. (2023) propose *L. minor* as a sustainable alternative for wastewater treatment. Its protein content reaching 18.84 mg/g (dry weight) at the end of the tests, makes it a promising resource for aquaculture and the food sector.

Although nanoparticles have become key players in biotechnological solutions, their widespread use in recent years and rapid accumulation raise concerns as potentially hazardous pollutants, posing significant environmental risks. Several species within the *Lemna* genus have been studied for their potential to remediate nanoparticles (NPs) or contaminants released by NPs (MOUSAVI-KOUHI, 2025). These current studies continue to demonstrate the great potential of *L. minor* in various forms of environmental remediation, from the removal of toxic compounds to the treatment of wastewater and sewage.

It is important to highlight that phytoremediation, in addition to removing pollutants, can reuse the extracted resources, together with the plants, for various applications. A promising example is biochemical conversion, a technology widely used for the production of multiple biofuels, such as bioethanol, biomethanol, biodiesel, Fischer–Tropsch diesel, and fuel gases, including biomethane and biohydrogen. These end products can be obtained through anaerobic digestion, alcoholic fermentation, and acidogenic fermentation of aquatic macrophyte biomass (HOSSAIN et al., 2010). In addition, bioremediation processes are directly linked to the metabolic capacity of the organisms used (Section 3.2.1), in which substrates are transformed into metabolites, which may include high value-added products or molecules, many of which have associated bioactivities for the pharmaceutical and cosmoceutical industries. Sayanthan (2024) analyzes how floating aquatic macrophytes contribute to the circular economy by efficiently removing contaminants from wastewater while generating biomass that can be used for bioenergy, fertilizers, and animal feed. However, the study highlights that the current use of this biomass is still limited and that more research is needed to optimize its applications and overcome the challenges in implementing this cradle-to-cradle concept for sustainable wastewater treatment and resource recovery.

Table 3. Phytochemicals, applications, and analytical techniques used in the analysis of *L. minor.*

Phytochemicals	Bioativityes	Aplications	Chemical analyzes	Authors
Fitosterols: (1-3), Amino acid: (4) (8), vitamin: (5), Flavonoides: (6), Fatty acid: (7),	Antioxidant	Food industrial	Gas Chromatography-Mass Spectrometry (GC-MS) and Metabolomics data analysis	Yahaya et al., 2022
Carotenoids: (9-10), Vitamin (5), Chlorophylls, Heavy metal content	Nr	Human or animal consumption	Proteins AOAC official Method 2001.11 (AOAC, 2002); lipids Gravimetric method of D'oca et al. (2011); Pigments and (Iliopoulou, et al., 2022).	Katsara et al., 2024
Methane concentration, Bioreactor #1 at 35 Days (from 0.7% to 12%), 45% at 48 days Biogas, Bioreactor No. 1: 0.025 Lg of organic carbon on day 35	NR	Biogas Potential	Component composition of the biogas was used directlty in the bioreactor using portable gas analyzer GA2000 Plus (Chusov et al 2019)	Chusov et al., 2022
Ácidos fenólicos: (13-22) Flavonoides: (23), (27-28); Polifenóis:(26-29); Taninos: (25); Outras classes: (11-12) (24); Spherical-shaped synthesized AgNPs with an average size of 40.56 nm (Faisal et al. 2020)	Activity against Sitophilus oryzae and Tribolium castaneum, pests of stored grains	Nanomaterial-based technologies in the pesticide industry.	High Performance Liquid Chromatography (HPLC); Scanning Electron Microscopy (SEM), Micrograph	Abdel-Megeed et al., 2023
556 identified compounds: Amino acids, Peptides, Benzenoids, Fatty acyls, Flavonoids, Glycerolipids, Glycerophospholipids, Organonitrogen and Organooxygen compounds, Phenolic acids, Stilbenes, and Terpenoids.	Antioxidant Microbiological	Improve meat product shelf-life and quality	Ultra-High Performance Liquid Chromatography (UHPLC) and Metabolomics data analysis	Rocchetti et al., 2023
Non-essential amino acids, including Ala, Arg, Asp, Cys, Glu, Gly, Pro, Ser, and Tyr, as well as non-proteinogenic amino acids like Cit and Tau. The Fatty acids:	Nr	Sustainable feed ingredient in aquaculture	Analytical Chemists (AOAC) International, which includes methods for moisture, ash, crude protein, and crude lipid analysis; Amino acid contents were analyzed using a dedicated Hitachi L-8900 High-Speed Amino Acid Analyz	Goswami et al., 2022

SFA; MUFA; PUFA, (n-6 PUFA) and α-linolenic acid.				
Crude protein, minerals, and fatty acids, pigments: palmitic acid	Nr	Aquaculture feeds	Crude Protein & Amino Acids: CP determined (APHA 2005; 4500-Norg); AA analyzed by ion exchange chromatography (Appenroth et al., 2017); Lipids & Fatty Acids: Extracted (Bligh & Dyer, 1959); FAME analyzed by GC-MS; Minerals (K, Ca, Mg, Cu, Fe, Mn, Zn): Measured by atomic absorption spectrophotometry (Malavolta et al., 1997); Photosynthetic Pigments: Carotenoids & astaxanthin quantified (Jeffrey & Humphrey, 1975; Lichtenthaler, 1987).	Heitzman et al., 2024
Phenolic Compounds (30-32), glucosinolates, and phytohormones.	Bio-stimulant	Fertilizer Industry	Ultra-high-performance liquid chromatography coupled with mass spectrometry (UHPLC-ESI/QTOF-MS)	Buono et al., 2022

Sitosterol (1), Stigmasterol (2), Campesterol (3), 5-Hydroxy-L-tryptophan (4), Tocopheryl acetate (5), Naringenin (6), α-Linolenic acid (7), Glutamic acid (8), Lutein (9), β-Carotene (10), Pyrogallol (11), Quinol (12), Gallic acid (13), p-Hydroxybenzoic acid (14), Vanillic acid (15), Syringic acid (16), p-Coumaric acid (17), Benzoic acid (18), Ferulic acid (19), Caffeic acid (20), Cinnamic acid (21), o-Coumaric acid (22); Catechin (23), Chlorogenic acid (24), Ellagic acid (25);Resveratrol (26), Rutin (27), Quercetin (28), Rosmarinic acid (29), 5-nonadecenylresorcinol (30), hydroxytyrosol (31), and 4-hydroxycoumarin (32). Non-essential amino acids, including alanine (Ala), arginine (Arg), aspartate (Asp), cysteine (Cys), glutamic acid (Glu), glycine (Gly), proline (Pro), serine (Ser), and tyrosine (Tyr), as well as non-proteinogenic amino acids like citrulline (Cit) and taurine (Tau). Saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA), primarily linoleic acid (n-6 PUFA) and alpha-linolenic acid (α-LA).

3.5. Chemical composition and Bioproducts of lemma minor

In addition to its applications already explored in the field of phytoremediation and as a biological model for substance toxicity testing, species of the *Lemna* genus present an interesting chemical arsenal (NATI et al., 2024), especially *L. minor* (ROCCHETTI et al., 2023). Its composition includes essential nutrients, such as proteins and lipids, which reinforce its nutritional value and its potential as a promising plant ingredient for future food products. Among its most explored potentials, its protein content stands out, making it a sustainable source of this macronutrient, with the capacity to replace animal meat, offering a healthier and more accessible alternative (APPENROTH et al., 2018). Studies have identified key phytochemicals in *L. minor,* including phytosterols, flavonoids, amino acids, acetic acid esters, and fatty acids (Figure 4), and phenolic compounds, polyphenols (Figure 5). In addition, non-essential amino acids and polyunsaturated fatty acids, including linoleic and α-linolenic acids, were found. The analytical techniques used to identify these compounds include Gas Chromatography coupled to Mass Spectrometry (GC-MS), High Performance Liquid Chromatography (HPLC), Atomic Absorption Spectrophotometry (AAS), Spectrophotometry for Photosynthetic Pigments and Amino Acid Chromatography (Table 4).

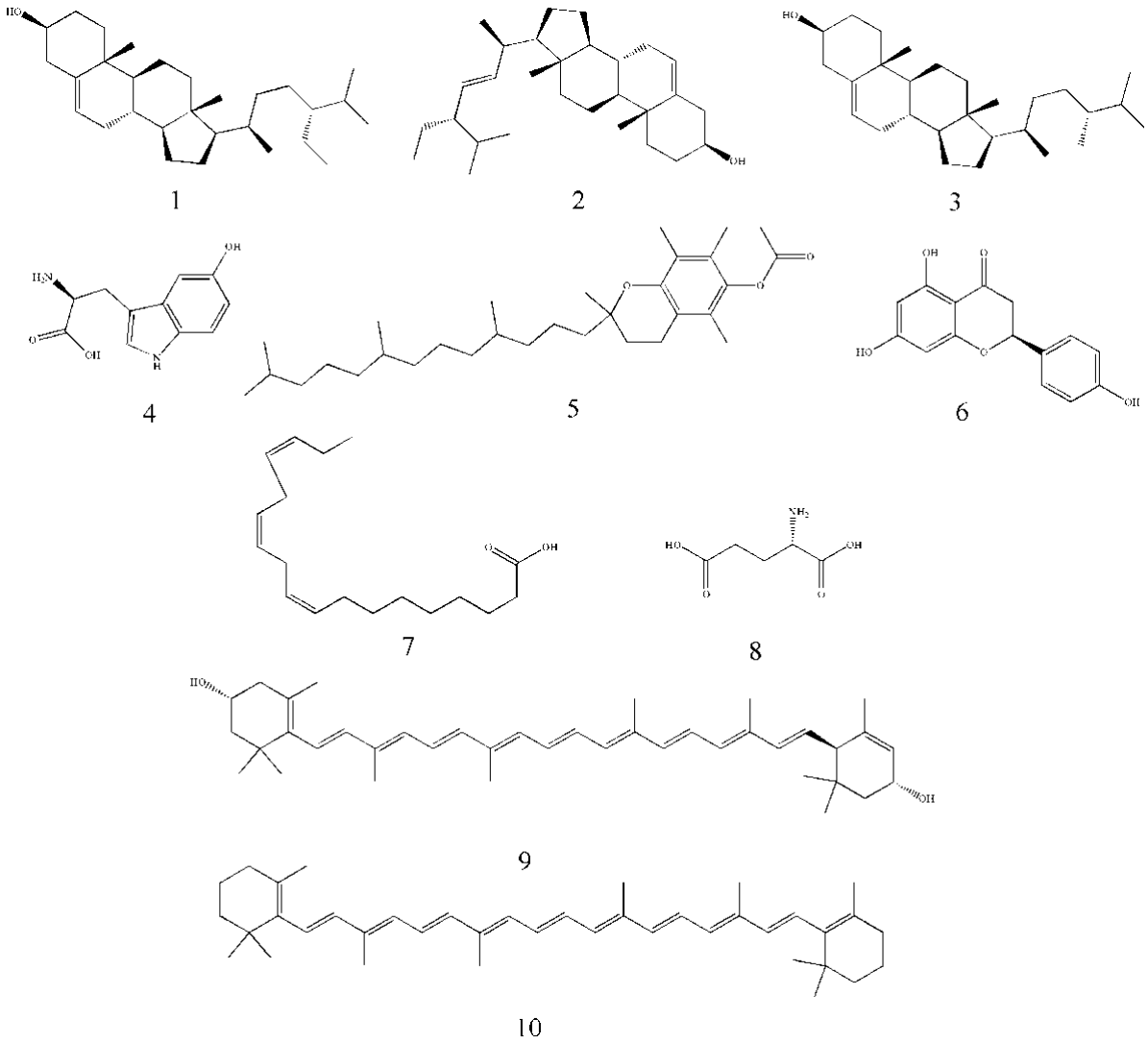


Figure 4. Phytochemicals found in L. minor: Sitosterol (1), Stigmasterol (2), Campesterol (3), 5-Hydroxy-L-tryptophan (4), Tocopheryl acetate (5), Naringenin (6), α-linolenic acid (7), Glutamic acid (8), Lutein (9), β-carotene (10).

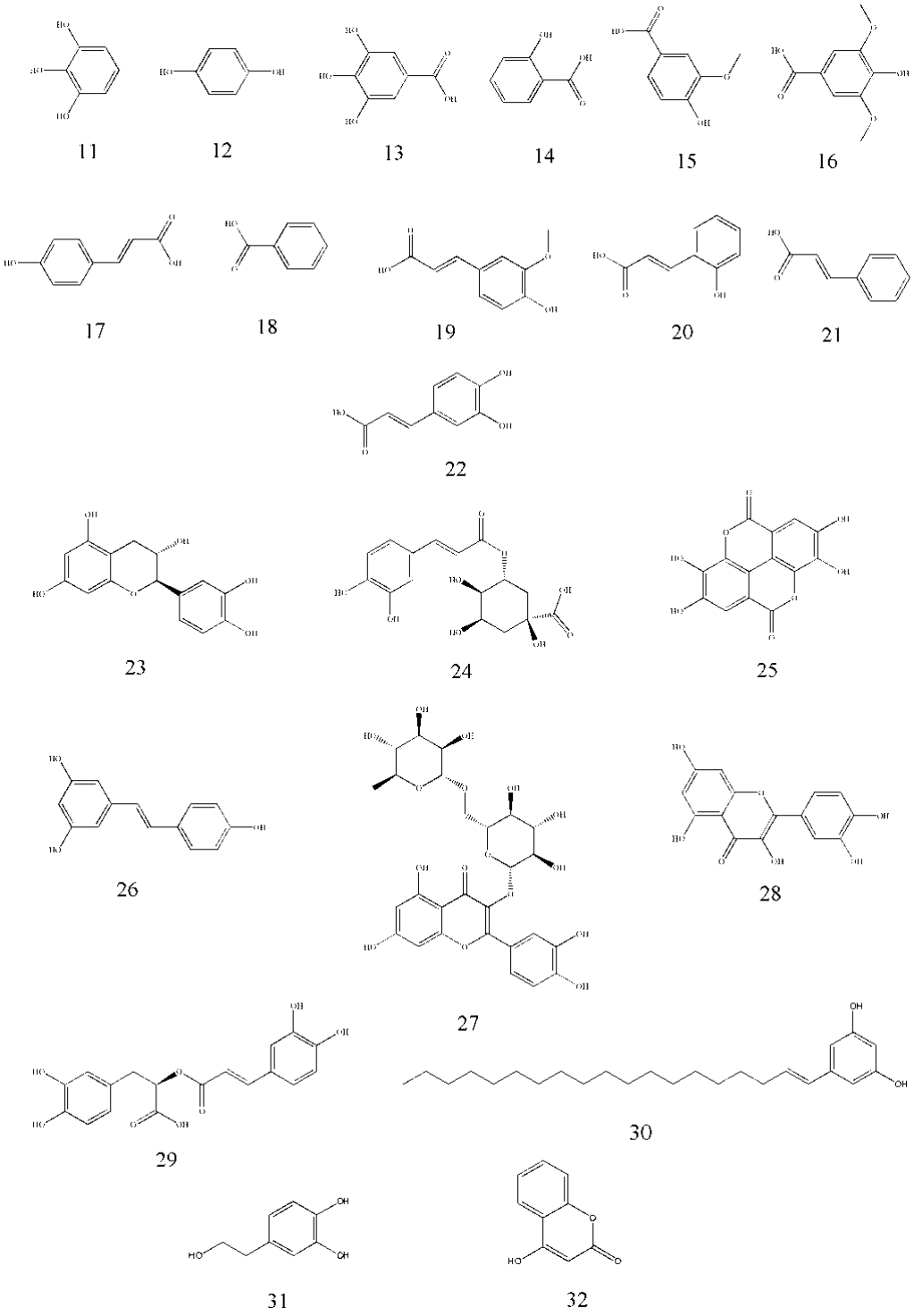


Figure 5. Phytochemicals found in *L. minor* : Pyrogallol (11), Quinol (12), Gallic acid (13), p-Hydroxybenzoic acid (14), Vanillic acid (15), Syringic acid (16), p-Coumaric acid (17), Benzoic acid (18), Ferulic acid (19), Caffeic acid (20), Cinnamic acid (21), o-Coumaric acid (22); Catechin (23), Chlorogenic acid (24), Ellagic acid (25); Resveratrol (26), Rutin (27), Quercetin (28), Rosmarinic acid (29), 5-nonadecenylresorcinol (30), hydroxytyrosol (31), and 4-hydroxycoumarin (32).

The studies discussed here highlight the rich chemical diversity of *L. minor,* which supports its potential for multiple applications. To better illustrate these findings, the studies are categorized into key areas such as *nutritional potential* and *technological and industrial innovations*, with key insights from each study outlined below. Importantly, the studies presented here incorporate more advanced analytical techniques, increasingly robust databases, and metabolomic tools, alongside more traditional techniques for macronutrient chemical analysis. These advances allow for a more detailed analysis of its metabolic profile, providing valuable insights into its composition and potential applications.

Nutritional potential: Regarding the exploration of its metabolic profile for applications in the food sector, Yahaya et al. (2022) focused on the identification of phytosterols in *L. minor*, its chemical profile along with protein contents ranging from 26.38% to 29.91% demonstrated the potential as a future food source due to its nutritional composition and microbial safety, they highlight that tocopherol determined in the samples has antioxidant properties beneficial to human health. On the other hand, a study by Katsara et al. (2024) explored the cultivation of *Chlorella sorokiniana* and *L. minor* in thermal waters for biomass production, trying to test the hypothesis that thermal waters could be used as a low-cost means for the production of microalgae and duckweed biomass for human or animal consumption. In their chemical profile analyses, they determined that both organisms contained significant amounts of lutein (up to 1378 mg/kg) and chlorophyll (up to 1518 mg/kg), while β-carotene and tocopherols were found in lower concentrations, not exceeding a few tens of mg/kg. Heavy metals were also determined, highlighting that *L. minor* accumulated higher concentrations of Cd, Cu, K, Mn, Na, Ni, and Zn. Finally, duckweed protein levels range from 35% to 43%.

Goswami et al. (2022), evaluated the nutritional value of *L. minor* for common carp (*Cyprinus carpio*) fingerlings with varying inclusion levels. Essential (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine), non-essential (alanine, arginine, aspartate, cysteine, glutamic acid, glycine, proline, serine, and tyrosine) and non-proteinogenic (citrulline, hydroxyproline, taurine, etc.) amino acids were determined, their fatty acid composition included saturated fatty acids (SFA) 23–26%, monounsaturated fatty acids (MUFA) 11–12%, n-6 polyunsaturated fatty acids (PUFA) mainly linoleic acid (LOA) 17–18% and n-3 PUFA

(α-linolenic acid) 41–47%. Highlighting again the content of crude protein (36.07%), crude lipid (8.45%) and ratifying once again its nutritional value.

These studies ratify the potential of *L. minor* as a valuable source of high-quality protein and beneficial fats, supporting its application in the food and nutritional sectors. The protein content in *L. minor* ranges from 26%-43%, with the highest levels. The lipid content is lower, typically between 8%-10%, with a notable presence of n-3 polyunsaturated fatty acids (PUFAs), ranging from 41% to 47%. In addition, the amino acid profile of *L. minor* includes a variety of essential amino acids, such as histidine, isoleucine, and lysine, as well as non-essential amino acids such as alanine, glycine, and proline.

Industrial and sustainable innovations: The reviewed studies highlight the versatile potential of *L. minor* across various sectors, demonstrating its broad applicability, including the synthesis of nanomaterials with pesticidal activity, sustainable energy production, food preservation, and the development of bioproducts, all while contributing to environmental solutions. Abdel Megeed et al. (2023), demonstrated significant insecticidal activity against stored product pests *Sitophilus oryzae* and *Tribolium castaneum* of synthesis of silver nanoparticles (AgNPs) from *L. minor.* The aqueous extract of plant contains various bioactive compounds such as amino acids, flavonoids, and organic acids, and fatty acids. Notably, HPLC analysis identified several significant compounds such as vanillic acid, benzoic acid, quercetin, and others, which play a role in the synthesis and stabilization of the AgNPs. The research highlights the eco-friendly production of AgNPs using plant biomolecules for stabilization.

Regarding the sustainable energy sector, a study that explored the energy potential of *L. minor* residual biomass for biogas production. The study identified the optimal mixtures to increase the biogas yield of duckweed biomass, reporting specific methane concentration yields (from 0.7% to 12%), with the highest specific biogas yield of 0.16 L/g organic carbon on the 48th day in the bioreactor (CHUSOV et al., 2022). On the other hand, in an industrial application in the food sector, with a specific focus on food preservation, duckweed extracts (DEs) were evaluated for their impact on the shelf life of beef burgers during 19 days of storage. The findings suggest a potential pro-oxidant role of DEs, affecting protein oxidation. Among those responsible for these activities, polyphenols (flavonols, flavan-3-ols and anthocyanins) stood out,

representing a significant part of the bioactive content (1222.07 µg DM), followed by terpenoids (514.17 µg DM). The phytochemical composition in this study also included essential amino acids (phenylalanine, histidine, lysine, valine and tryptophan), supporting their use in food applications (ROCCHETTI et al., 2023).

A recent study on circular economy focused on utilizing a nature-based solutions (NBS) model that integrates fish and macrophytes to assess methods for reducing effluent discharge containing nitrogen compound. The chemical profile of *L. minor* revealed a high crude protein content, ranging from 20% to 45% on a dry weight basis, the total lipid content was 92.32 mg g^-1, with 43.67% saturated fatty and 30.69% polyunsaturated fatty acids (PUFA). The study also noted a favorable n-6: n-3 ratio of 0.93, indicating its potential as a valuable source of beneficial fatty acids for dietary and bioproduct applications (HEITZMAN et al., 2024).

Finally, Buono et al. (2022) evaluated the potential of an aqueous extract of *L. minor* as a biostimulant for corn metabolomic profiling determined a total phenolic content of 6714.99 mg kg^{-1}, known for its antioxidant properties. In addition, the extract includes glucosinolates (4563.74 mg kg^{-1}), such as n-(E) ω-(methylsulfanyl)alkanoate oxime and ω-(methylsulfanyl)-2-oxoalkanoate, which contribute to plant defense and growth stimulation, in addition to phytohormones, including auxins, cytokinins, and gibberellins.

The reviewed studies demonstrate its diverse and promising potential in several sectors. Nutritionally, *L. minor* offers a rich protein content ranging from 26% to 43%, along with essential amino acids and beneficial fats, including n-3 polyunsaturated fatty acids, making it an attractive option for food and feed applications. On the other hand, bioactive substances, such as tocopherols, glucosinolates and phenolic compounds, increase its value as a source of functional food with antioxidant and biostimulant properties. It is important to emphasize that in these studies, industrial applications such as the ecological synthesis of silver nanoparticles with pesticide activity and its potential in the production of sustainable energy through biogas draw attention due to their high technological level. Therefore, research into this multifaceted resource with significant environmental, nutritional and industrial benefits should be promoted.

In this work, we review how the valorization of the chemical profile of *L. minor* results in several applications, including the extraction of sustainable products from its biomass. However, when considering the large-scale production of biomass or products using environmentally efficient techniques, it is inevitable that the biorefinery

process generates waste. As previously discussed, these so-called "industrial wastes" may contain remaining bioactive compounds or other components with added value. These materials can be exploited, for example, in the production of cellulose nanoparticles, using specific advanced technologies (PUGLIA et al., 2024) by associated companies or industrial sectors dedicated to waste management. Thus, the conversion of these residues into co-products not only allows the optimization of the use of biomass, but also contributes to the minimization of environmental impacts, promoting the implementation of more sustainable production chains.

3.6. Cultivation strategies of L. minor

Studies conducted in several countries stand out for their use of *L. minor* in technolog cultivation conditions and experimental contexts. Based on the results obtained, we can see that research is concentrated in countries such as Germany, Japan, Russia, Poland, Iran, Malaysia, Italy and Turkey. In this sense, it is essential that similar experiments be encouraged in Latin American countries, especially in Brazil. Expanding studies in this technolo will allow a deeper understanding of the potential of this plant in technolog geographic zones. From the reviewed studies, key information on cultivation conditions was organized for better understanding, including data on cultivation time, light intensities, growth/growth rate, culture techno, treatment variables, and physiological and biochemical measurements used to evaluate the cultivation systems (Table 4).

Table 4. Cultivation conditions and experimental variations in studies with *L. minor.*

Cultivation time	Light intensities (lux or µmol m−2 s−1)	Growth /Growth rate	Culture medium	Treatment Variables	Physiological and Biochemical Measurements	Author
3 days Pre-cultivation. Experiments lasted for 7days	50, 100 and 150 µmol m−2 s−1	RGR: 150–70/30 (0,13 ± 0,013 d^{-1})	Nutrient medium: Comprised of commercially available fertilizers. Key elements: NO_3^--N, NH_4-N, PO_4^{3-}, K, Mg^{2+}, SO_4^{2-}, Ca, Cl^-, Fe^{3+}, $B_3O_3^-$, Mn^{2+}, Zn^{2+}, Na. Nutrient dosing: Set to an electrical conductivity (EC) of 0.6 mS cm^{-1}	Three distinct light intensities used. Spectral distributions: Red light: 660 nm Blue light: 450 nm 20% white light (6500 K) maintained in all experimental conditions	RGR; CPC, RPY and chlorophyll content.	Petersen et al 2022
Optimization Experiments:18 days. Harvest cycles: 3 or 5 day; and long-term times	Adjustable wavelengths: 400nm, 440nm, 660nm, 730nm Additional: 3,000K white-light emitters Specific LED emitters for PAR illumination Photoperiod: 16/8 (light/dark)	Regrowth rate: Laboratory Setup in Bon: 216 g FMm-2d-1 at 400 ppm CO2; Upscaled Technicum System in Kalkar: 173 g FMm-2d-1; Second Upscaled Stacked Cultivation System in Berlin: 190 g FMm-2d-1	Modified Hoagland solution: NH_4 added as $(NH_4)_2SO_4$. Micronutrients: Supplied in specific forms: H_3BO_3; $MnCl_2 \cdot 4H_2O$; $ZnSO_4 \cdot 7H_2O$; $CuSO_4 \cdot 5H_2O$ $Na_2MoO_4 \cdot 2H_2O$; $MgSO_4 \cdot 7H_2O$ $Ca(NO_3)_2 \cdot 4H_2O$; Fe-EDDHA	Nutrition: NH4+/NO3- ratio, Phosphorus (P), Potassium (K), Magnesium (Mg) and Calcium (Ca) concentrations; Light: Light intensity and light spectrum; CO2 concentration.	Regrowth Rate, Biomass Cover, Biomass Yield, Protein Yield, Harvest Intervals, Harvest Range.	Schmidt and Goldbach 2022

10 and 30 days	75 µmol m−2 s −1 Photoperiod: 16/8 (light/dark)	1.3-folds and dry weight up 1.7-folds	Modified Hoagland medium, mH, (Suzuki et al., 2014).	Presence of Bacteria: Co-cultivation with A. vinelandii (gnotobiotic and mutant); Co-cultivation with (Acinetobacter calcoaceticus, Pseudomonas fulva, Ensifer sp.); Suspension and fixation experiments (addition or adhesion of bacteria). Nitrogen Conditions: Medium with and without nitrogen	Frond Counting, Dry Weight; CPC, Starch Content, Nitrogen Fixation Activity (ARA), Phosphate Solubilization Activity, Siderophore Production Indole-3-Acetic Acid (IAA) Production, Biofilm Formation	Sajjad et al 2023
7days	8000 lux (cool white light of fluorescent lamps). Photoperiod: 16/8 (light/dark)	After irradiation with 18 Gy and exposure to copper, the SGR decreased to 40% (3 µmol/L Cu), 50% (5 µmol/L Cu), and 56.5% (6.3 µmol/L Cu)	Steinberg's medium (Steinberg 1946)	Non-irradiated plants and plants irradiated with 18 Gy, 42 Gy and 63 Gy, at different copper concentrations (0, 3, 5, 6.3 µmol/L).	SGR.; Copper Accumulation; Frond Area; Frond Damage; Photoassimilatory Pigments (Chlorophyll and Carotenoids)	Bodnar e Cheba 2020
Natural conditions: Harvest after 2.5 months. Laboratory conditions:	Two T8 fluorescent lamps (HAGEN®, Germany): AQUA-GLO (120 lx, 18,000 K, for chlorophyll a and b)	Nr	Aquarium water: Purified with an internal filter (Pat-Mini, Aquael, Poland); Fertilizer (FLOURISH, SACHEM, USA):	Growing Environment: Natural (pond) vs. laboratory (aquarium); Lighting Conditions: Natural sunlight vs. controlled artificial;	Nutrient Analysis: DM, CPC, CT; CA Amino Acid Analysis; Fatty Acid; Mineral Elements Analysis: Macro (Ca, K, Mg, Na, P), Trace Elements (Cu, Zn), Heavy Metals (Cd, Pb).	Miltko et al 2024

Harvest after 1 week.	and SUN-GLO (210 lx, 4,200 K, warm white light); Photoperiod: 20/4 (light/dark)		Applied twice a week (3 ml). Nutrient composition: N: 0.07%, PO_4^{3-}: 0.01%, K: 0.037%, Ca: 0.14%, Mg: 0.10% S: 0.27%, B: 0.008%, Co: 0.0004%, Cu: 0.0001%, Fe: 0.32%, Mn: 0.0118%, Mo: 0.0009%, Zn: 0.0007%	Temperature: Natural range vs. controlled temperature (25°C); pH: Natural range (6.9-7.1) vs. controlled range (6.5-7.3)	Tocopherols and Tocotrienols Analysis.	
Acclimatization: 1 week. Sample Collection: 12, 24, 48, 72, 96, 144, and 168 hours. Total Duration: 7 days.	74 µmol m−2 s −1 Photoperiod: 16/8 (light/dark)	Nr	Autoclaved half Hogland media for one week (Hagland and Arnon 1950)	The concentration of hexavalent chromium (Cr (VI)); various concentrations (0, 1, 10, 50, and 100 mg L −1)	Photosynthetic pigment content, total phenolics, flavonoids, MDA conten; Proline Content: Reducing Sugars and Polysaccharides; Lignin Content; Hydrogen H2O2 Levels	Aslanzadeh et al 2024
Acclimatization: 14 Days; Experimental Duration: 7 days.	1600 lux. Exposure to continuous white light	SHPA had an RGR of 0.0909 day^{-1}, while SHPAM had 0.0679 day^{-1}. The control's RGR was only 0.0418 day^{-1}	Hoagland nutrient medium and left to acclimatize for 14 days before the start of the study (Nesan et al., 2020)	Three different cultivation setups: Control: Conventional glass jar with a smaller surface area; SHPA: Superhydrophobic (SHP) coated acrylic sheet; SHPAM: SHP coated acrylic sheet with an aluminum mesh placed centrally.	RGR; Total Protein Content; Total Chlorophyll Content; Total carbohydrates; Crude lipid percentages; Chlorophyll Content Dynamics:	Chua et al 2023

Duration: 30 days. Analysis Points: Day 0, Day 10, Day 20, and Day 30.	7000 lux Photoperiod: 16/8 (light/dark)	After 30 days, group 5 doubled its green biomass, while groups 2, 3, and 4 showed the highest increases. Groups 0, 1, and 9 exhibited stagnation or reduction (The number of duckweed plants)	Liquid fraction of pig slurry: Collected from a farm where pigs were fed a cereal feed mixture, supplemented with protein (soybean meal and rapeseed meal) and a mineral-vitamin premix.	The experiment tested pig slurry concentrations diluted in water to create growth media, ranging from 2.0% (Group 1) to 0.03% (Group 9), with a control group (0%) using pure water.	Growth Medium Analyses; Chemical composition (protein, lipid, ash content, Crude Fiber, Macro and Microelements, Nitrogen Species, Heavy metals, Amino Acids and Fatty Acids); Temperature of growth medium; Total dissolved solids (TDS); Electrical Conductance (EC) Measurement; pH levels.	Sonta et al 2023
Plant Growth: 8 weeks. Corn seed treatment: 8-hour priming with L. minor extract. Germination: 4–5 days. Hydroponic growth: 21 days for growth and nutrient analysis.	100 µmol m −2 s −1 Photoperiod: 12/12 (light/dark)	Nr	Sterilized nutrient solution (pH 6.5) composed as follows: 3.46 mmol L−1 KNO3, 1.25 mmol L−1 Ca (NO3)2·4H20, 0.66 mmol L−1 KH2PO4	The maize seeds were treated with varying concentrations of duckweed extract during the seed priming process. The concentrations tested were 0.00% (control), 0.01%, 0.05%, 0.50%, and 1.00%.	Germination Rate; Radicle Length; Leaf Area; Chlorophyll Content; Biomass Production; Vigor Index; Nutrient Assimilation.	Buono et al 2022
Culture medium optimization: 12 days. Cultivation in different solutions: 9 days.	Nr	Solution 10 to 12 days: 5g of DM%	Hoagland solutions with: Macro-elements: KH_2PO_4, KNO_3 Ca $(NO_3)_2 \cdot 4H_2O$, $MgSO_4 \cdot 7H_2O$	The study specifically manipulated the concentrations of macro-elements like potassium (K) and phosphorus (P)	Total dry matter, protein content, and total ash content; Concentration of Macro-Elements.	Ayça and Ersu 2023

	Fe^{3+}. Trace elements: H_3BO_3, $MnCl_2 \cdot 4H_2O$, $ZnSO_4 \cdot 7H_2O$ $CuSO_4 \cdot 5H_2O$, $H_2MoO_4 \cdot H_2O$ Source: All purchased from Sigma Aldrich (St. Louis, MO, USA).

Parameters: Relative Growth Rate (RGR), Specific Growth Rate (SGR), Crude Protein Content (CPC), Relative Protein Yield (RPY), Dry Matter (DM), Crude Fat (CT), Crude Ash (CA), Malondialdehyde (MDA), and Peroxide (H_2O_2

Studies on the cultivation of *L. minor* range in scale from small laboratory experiments to large-scale systems. On a small scale, has been cultured using 5 mL glass vials with bacterial inoculation (SAJJAD et al., 2023), in 100 mL bottles from plants collected from Saravan Lagoon, Iran (ASLANZADEH et al., 2024), on acrylic-coated cultivation platforms with surface tech of 352.5 cm2 with na average volume of 150 mL (CHUA et al., 2023), in 500 mL PET bottles with Hoagland's solution (AYÇA & ERSU, 2023) and in a KBWF 240 climate chamber (BODNAR & CHEBA, 2020). Using a 55echno-scale approach was cultured in a 5 × 3 × 3 m container (PETERSEN et al., 2022), in 120 × 40 × 30 cm technol with sediment substrate using plants collected from a lake near Serock, Poland (MILTKO et al., 2024), in 30 plastic containers of 14 L each (SONTA et al., 2023), in 35 × 28 × 14 cm polyethylene trays (BUONO et al., 2022). On a large scale, *L. minor* strains have been studied and cultivated in systems such as the Scaled Technicum System with 302 m² of aquatic culture surface in Kalkar and the Upscaled Stacked Cultivation System in Berlin (SCHMIDT & GOLDBACH, 2022).

The studies used technolog photoperiod and temperature conditions to evaluate its growth. Among the variations, the most common photoperiod is 16 hours of light and 8 hours of darkness (16h/8h), with some exceptions, such as a 20h/4h photoperiod or continuous exposure to techn light. Cultivation temperatures range from 23°C to 29°C, with some research using specific controlled temperature conditions, such as 24°C or 25°C ± 2°C, while in some studies the information on temperature (nr) is not revealed.

These investigations span a wide range of topics, from the effects of environmental stressors like heavy metals and radiation to the manipulation of growth conditions to boost protein content and overall biomass. Por example, the results of Aslanzadeh et al. (2023) indicated that *L. minor* was efficient at removing Cr(VI) at lower concentrations, although the efficiency decreased at higher concentrations. Oxidative stress was evident through increased H_2O_2 and MDA levels, while the accumulation of polysaccharides and phenolic compounds suggested stress-induced metabolic adjustments. Ayça et al. (2024) determinated that the macroelements KH_2PO_4 and Ca $(NO_3)^2$ significantly contributed to the increase in protein content, with optimal conditions leading to an increase from 39.81% to 51.09%. The modified Hoagland solution achieved a higher protein content (41.74%) compared to the commercial solution (33.01%).

Furthermore, Bodna and Cheban (2022) showed that the combination of gamma radiation and copper had a synergistic effect, reducing the growth rate and increasing lipid peroxidation. While, other study showed that superhydrophobic cultivation platforms SHP platforms resulted in higher relative growth rates (RGR), protein, carbohydrate, and lipid content compared to traditional cultivation in glass vessels. Additionally, the SHP platforms led to greater biomass productivity, indicating their potential for improving *L. minor* cultivation efficiency (CHUA et al. 2023). Moreover, comparing cultivation in laboraory and field conditions, it was demonstrated that the amino acid composition was higher in laboratory-cultivated plants, while natural environment plants showed greater levels of polyunsaturated fatty acids (MILTKO et al. 2024).

Some results indicated that light intensity had a significant impact on growth and productivity, providing insights into optimizing cultivation conditions for higher biomass and protein yields. Petersen et al. (2022). Finally, Sajjad et al. (2023) evaluated the effect of the nitrogen-fixing bacterium *Azotobacter vinelandii* A81 and showed that it significantly increased the growth and nutritional content of *L. minor,* making it a promising approach to improve the productivity and nutrient content of aquatic plants used in various applications. These reviewed studies highlight the importance of optimizing cultivation conditions to maximize productivity and nutritional quality of *L. minor.* The findings suggest that factors such as nutrient medium composition, light intensity, and environmental stressors can significantly influence plant growth, biochemical content, and stress responses. Furthermore, novel cultivation platforms and the use of beneficial microorganisms have demonstrated potential to improve growth and nutrient content this plant. These findings should encourage future research proposals for improving cultivation practices in different scenarios, as this will impact the exploration of new biotechnological solutions to harness the full potential in various applications

Cultivation and maintenance strategies represent one of the most critical aspects in the development of models based on the circular economy and sustainability (Figure 6). This is due to the need to consider in an integrated manner the economic and environmental impacts at all stages, from laboratory processes to production scaling, including the efficient management of by-products and waste generated.

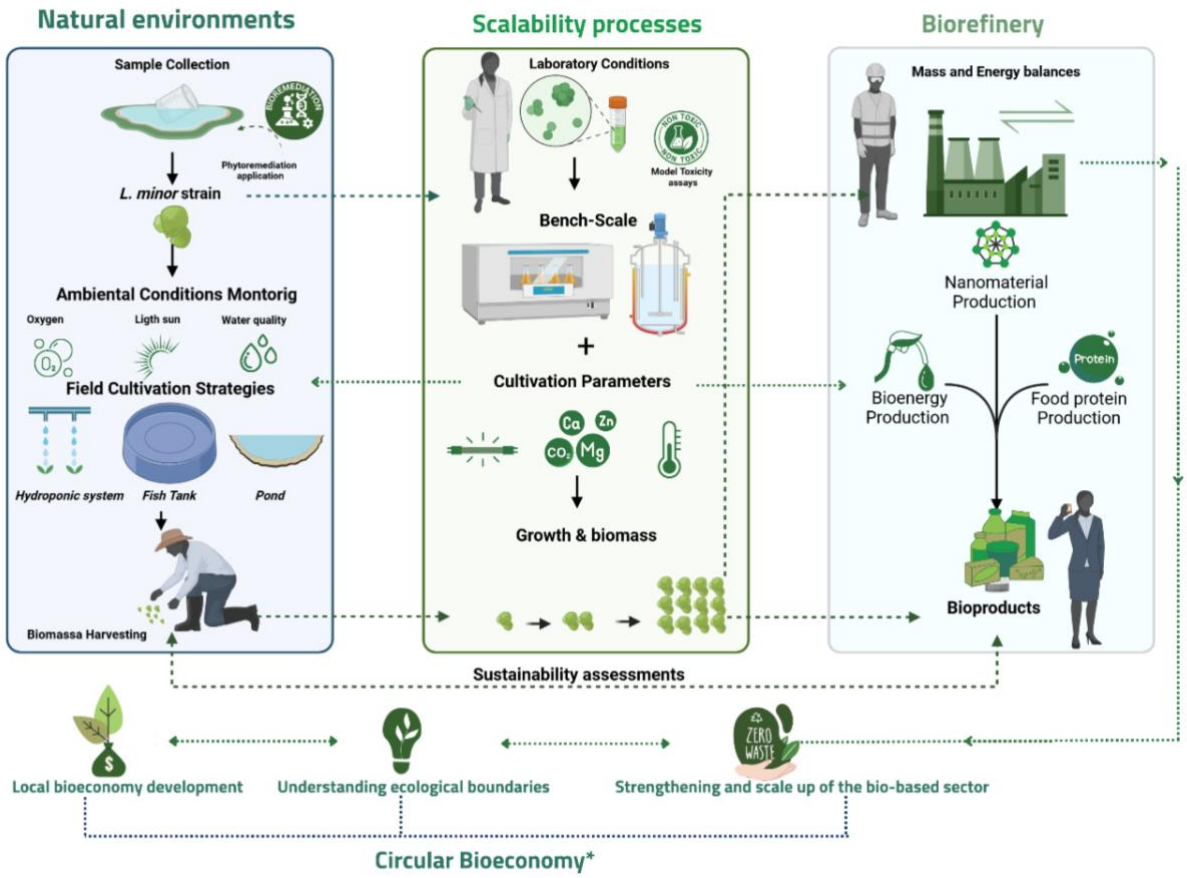


Figure 6. Laboratory cultivation strategies and parameters. The essential basis for processes in natural environments, scalability and biorefinery. Optimizing growth and biomass in the laboratory is crucial for maximizing the sustainable use of *L. minor* products, benefits, and applications in various scenarios.

The implementation of strategies that favor the transition to low-waste industrial chains must be planned from the initial stages of development, including the choice of cultivation medium, the definition of abiotic parameters and the treatment of variables to ensure the standardization and quality of the products obtained. The comparative analysis of experimental data collected over the years in the laboratory by researchers is essential to support innovative and regenerative solutions, reinforcing sustainability and environmental responsibility in the production of bioproducts. Ujong et al. (2025), worked on a general overview of other species of the genus *Lemna* cultivated in systems ranging from open tanks to controlled approaches with laboratory techniques and advanced technologies, driven by the search for more efficient and sustainable biomass production. This study highlights the advantages and challenges of these

cultivation systems but emphasizes that more research is still needed to optimize treatment and cultivation processes.

Aiming to provide more options for the organism to be used, not only as a source of bioprospecting, but also as an integrated part of business models, we cannot ignore the fact that startups are already exploring different species of duckweed to drive innovation in the sustainable food sector. Companies such as Plantible Foods (USA) use technology to extract the RuBisCO protein, creating plant-based egg substitutes. Hinoman (Israel) developed Mankai, a high-protein variety, promoted as a "super vegetable". Parabel (USA) produces the LENTEIN protein for supplements and functional foods, with a focus on sustainable processes. In Mexico, microTERRA combines cultivation in aquaculture systems with innovative flavor masking technologies, improving the acceptance of plant proteins. These startups exemplify the growing transition to sustainable protein alternatives, aligned with the principles of the circular bioeconomy. This information opens doors and creates opportunities to be explored in future review studies, in which the integration of concepts such as entrepreneurship, technological innovation and circular business models using *L. minor* can be highlighted, in addition to exploring the challenges faced, such as production optimization and consumer acceptance.

4. CONCLUSIONS

In the studies analyzed, the increasing incorporation of molecular techniques to define the taxonomic status of *L. minor* was observed, which completes the traditional systematic keys. The use of molecular tools, such as DNA barcoding (atpF-atpH spacer), AFLP, β-tubulin intron length polymorphism for hybrid identification, whole genome sequencing and cytogenetic techniques, has provided significant data in this area. Understanding the taxonomic status of this species is essential to drive biotechnological innovations of this plant in several applications.

Although phytoremediation and toxicity applications have been extensively studied and reviewed, we provide an updated overview of the compounds evaluated for toxicity, including emerging concerns such as nanomaterials and microplastics. Furthermore, we highlight the use of *L. minor* in phytoremediation for Contaminants of Emerging Concern (CECs), demonstrating that these are active and expanding areas that can represent a robust basis for the development of ecotechnological products.

The nutritional potential of *L. minor* has been reiterated over the years, consolidating it as a relevant source of nutrients. However, by evaluating its metabolic profile with modern analytical techniques, we have been able to build an increasingly complete and robust chemical profile, revealing its metabolic capacity. As new molecules are elucidated, opportunities arise for the development of innovative bioproducts, with important industrial implications. It is worth mentioning that the integration of applications such as bioremediation and the obtaining of products with high biotechnological and nutritional value should be encouraged, allowing the use of this plant within a circular economy model.

The information collected, organized and analyzed on cultivation conditions and strategies is crucial for the improvement of bioremediation techniques and ecotoxicity models. Furthermore, they play a fundamental role in optimizing the production of biomass and metabolites of interest. Understanding how biotic and abiotic factors interact under in vitro and field conditions allows the development of more efficient and sustainable practices, thus enhancing the biotechnological potential of *Lemna minor* to foster Eco-innovation and bioeconomy.

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CAPÍTULO II

Duckweed application in nature-based system for water phytoremediation and high-value coproducts at family agrisystem from a circular economy perspective

ABSTRACT

Duckweeds are widely recognized for their efficiency in the phytoremediation of agricultural and industrial effluents. This study had two main objectives: 1) Implement a Nature-based Solutions (NBS) utilizing the environmental services of duckweeds to improve water quality through phytoremediation in small fish farms; 2) Analysis of duckweed biomass produced in these fish farms to develop coproducts from a circular economy perspective in family agrisystems in the Brazilian Atlantic Forest. The effectiveness of the phytoremediation system was assessed by the reduction of the Trophic State Index (TSI). Phytoremediation in small fish farming NBS was implemented using *Clarias gariepinus,* employing two different managements approaches: (i) System I – *L. minor* cultured every 15 days, with biomass harvest and effluent analysis conducted in each cycle over 60 days; (ii) System II – *L. minor* cultured every 30 days, following a similar cycle and analysis. Additionally, effluent from fish production was tested for phytoremediation in a batch system in a climate-controlled laboratory. *L. minor* demonstrated efficiency in System II, leading to a reduction of the TSI. The dry biomass of the plants emerged as a viable source of amino acid for application in functional foods and feed or nutraceuticals. The findings underscore the potential for integrating *L. minor* into the NBS system and generating new co-products from circular production. In addition to its effective phyto-remediation properties, *L. minor*'s dry biomass exhibited appealing characteristics, with elevated levels of crude protein, minerals, fatty acids, and carotenoids. This positions *L. minor* as a promising candidate for developing bioproducts tailored for functional foods and nutraceuticals. This underscores the potential of duckweeds to produce valuable nutritional compounds beyond their remediation capabilities.

Keywords: Plant protein, Bioremediation, Bioproducts, Trophic State Index, *Lemna minor*.

1. INTRODUCTION

The global market is increasingly demanding higher-quality food and more sustainable production practices. Furthermore, the food industry increasingly emphasizes safety, social responsibility, and sustainability. As a result, the demand for healthy foods has increased in recent decades, leading to the global market for fish.

In 2020, global fisheries and aquaculture production reached an all-time high of 214 million tons (FAO, 2022). Aquaculture grew by 5.7% in seaweed and aquatic animal farming, reaching 122.6 million tons worldwide (FAO, 2022). In Brazil, fish farming also grew, producing 841.005 tons of fish in 2021, a 4.7% increase from the previous year. Notably, tilapia production accounted for 534.005 tons of this total, consolidating Brazil's position as the fourth largest tilapia producer in the world (Peixe BR, 2022). This trend towards increased production is a positive sign for the Brazilian aquaculture industry and highlights the potential for further growth.

While using more intensive production systems can increase fish production, it comes with environmental and economic risks. These systems are more susceptible to factors that affect production and require careful management to mitigate those risks (Knowler et al., 2020). Improper disposal of effluents generated by aquaculture is a risk, as it can lead to eutrophication and environmental problems due to the high load of nutrients eliminated, mainly phosphorus and nitrogen (Boyd et al., 2020). So, it is essential to implement effective management practices and prioritize sustainable production methods.

One promising alternative for reducing the environmental impacts caused by aquaculture is the implementation of integrated multitrophic aquaculture (IMTA) or similar systems that employ a circular economy and bioeconomy approach (Chopin et al., 2001; Knowler et al., 2020). IMTA combines the cultivation of aquatic organisms that require a food supply to grow with others that use the organic and inorganic matter dissolved in the water, creating a more balanced and sustainable system (Chopin et al., 2001; Troell et al., 2009). This approach allows for more efficient use of resources, reduces waste, and minimizes the potential for environmental impact (Troell et al., 2009). By employing IMTA, aquaculture producers can help ensure long-term sustainability by mitigating the risks associated with intensive production systems.

In this context, *Lemna minor*, commonly known as "duckweed", is a cosmopolitan aquatic macrophyte used in IMTA systems to reduce the potential

environmental impact caused by aquaculture effluent (Leng, 1999; Walsh et al., 2021). It mitigates ecological effects and can be an essential co-product of diversification. Duckweed produced in environments with high nitrogen and phosphorus content is a rich source of proteins, lipids, carbohydrates, omega-3, and omega-6, making it a nutritious food source for animals and humans (Appenroth et al., 2017). In underdeveloped countries, fresh biomass is primarily used for fish, poultry, and cattle nutrition, reducing the costs of commercial feed and providing a source of animal protein for family communities as a means of subsistence (Acosta et al., 2021; Fourounjian et al., 2020; Leng, 1999). In the plant-based food for the human sector, dry biomass is marketed with high added value (Acosta et al., 2021; Fourounjian et al., 2020).

Although *L. minor* is highly effective in uptaking nutrients from the water, its rapid development in natural and eutrophic aquatic environments can cause blooms that cover the surface and prevent the entry of light, harming the ecosystem's functioning (Walsh et al., 2021). Despite this potential negative impact, studies show that the use of Lemnaceae presents high efficiency in bioremediation processes for the treatment of effluents from aquaculture, wastewater, and pig farming (Cerqueira, 2021; Fatobete et al., 2019; Graeff et al., 2007; Mohedano, 2004; Oliveira, 2013; Pires et al., 2003; Tavares, 2004).

Thus, in this study, we incorporate the *L. minor* in the IMTA system can diversify production and provide new bioproducts. Therefore, this study aims to produce valuable nutritional compounds of duckweed and reduce the discharge of high nutrient effluent to the environment, contributing to a circular economy and a sustainable future in aquaculture. Using an IMTA model with fish and macrophytes, we evaluated the processes for reducing environmental problems related to nutrients dissolved in the effluents of the production system. We also assessed the diversification of production and chemical characterization of the plant biomass to show the potential use of *L. minor* integrated into an IMTA system to treat effluents and generate new bioproducts.

2. MATERIAL AND METHODS

2.1. Study Site and Experimental Design

The study was conducted in three family units in the rural area of Cajati, located on the southern coast of the State of São Paulo, a region with Brazil's largest fragment of the Atlantic Forest.

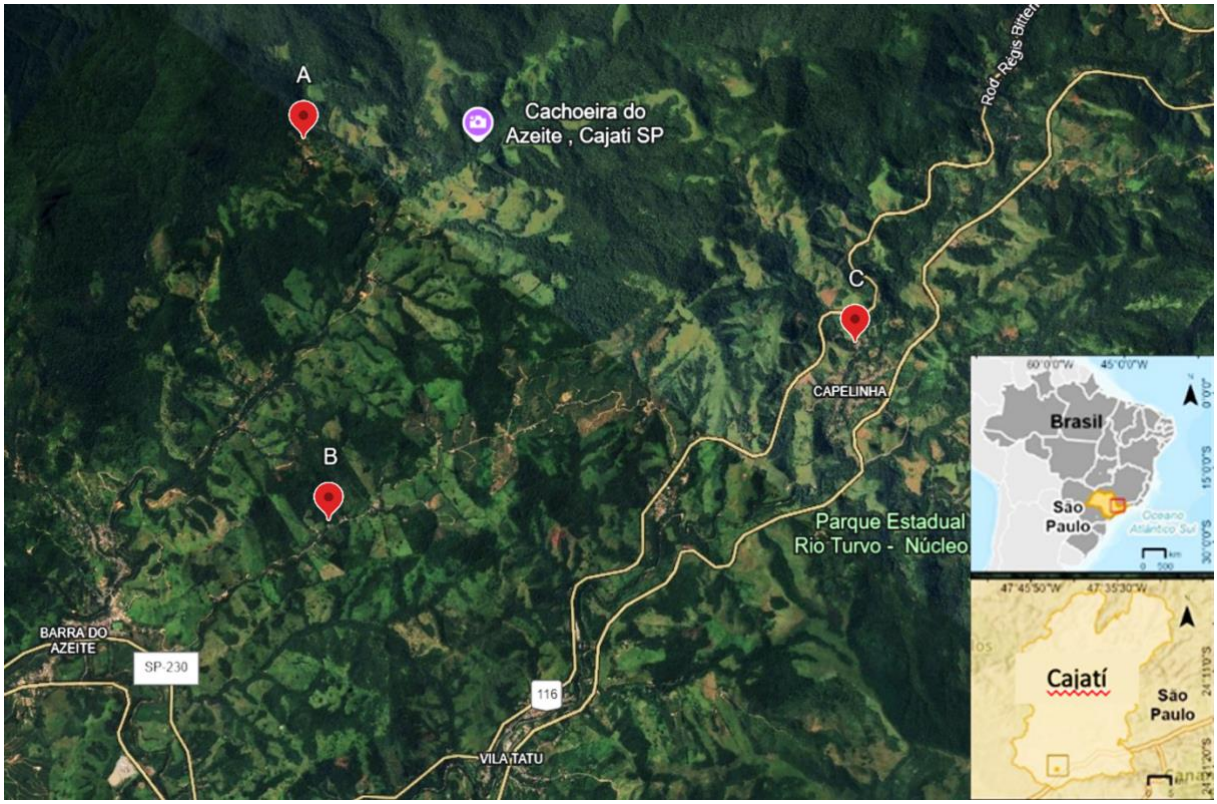


Figure 7. Location where the Study was carried out in the traditional Quilombola community, municipality of Cajatí, state of São Paulo, Brazil.

Clarias gariepinus, a catfish from the Clariidae family, was produced in an elevated circular tank of High-Density Polyethylene of 20 m³, with 5.91 m in diameter and 1.20 m in height. The system was maintained by a continuous water flow from a local river, with a flow rate of 0.27 m³/h. Starting in October 2019, 2.200 *C. gariepinus* alevins were introduced per tank, with an initial weight of approximately 6 g and lengths between 8 cm and 10 cm. The production cycle of *C. gariepinus* had 12 months. Feeding was carried out three times a day, initially with an extruded ration of 40% crude protein and at the end of 32% crude protein in *an ad libtum* regime. The fish was traded live from 850 g to pay-to-fish in the south and southeast of the country, and the sale price varied between US$ 1.50 and 2.50 per kilogram of live fish.

To implement the IMTA system, two circular tanks with a capacity of 500 L each were installed beside the fish culture tank for growing *L. minor*. These tanks received effluent water from the culture tank, which supplied the necessary nutrients for the plant's growth (Figure 8).



Figure 8. A) Conventional *Clarias gariepinus* farming system used by family-run farms; B) Settling tanks used in the production of *C. gariepinus*; C) Effluent generated at the end of the production process and *Lemna* Biomass; D and E) Harvesting and final production of *C. gariepinu*s on family farms in the Atlantic Forest region – São Paulo, Brazil (Heitzman, 2022).

2.2. Evaluation of Bioremediation

2.2.1. Bioremediation in a continuous flow system

The experiment was conducted using a completely randomized design in triplicate, with each family unit (FU) in the IMTA system considered an experimental unit. A 20 m³ circular tank of High-Density Polyethylene (HDPE) was used as the control with liquid effluent from fish production. The treatment group consisted of two

polyethylene circular tanks, each containing 500 L of water with a one m² water mirror for growing *L. minor* by FU. The decantation system continuously transferred liquid effluent from fish production to the treatment tanks.

System I – *L. minor* culture interval of 15 days

Each tank in the decantation system was initially seeded with 15 g of fresh *L. minor* biomass. Cultivation occurred every 15 days during winter (from 06/21 to 08/18/21). After 15 days, the total new biomass was harvested, and effluents were collected for physical-chemical analysis. This cycle was repeated for 60 days (Figure 1).

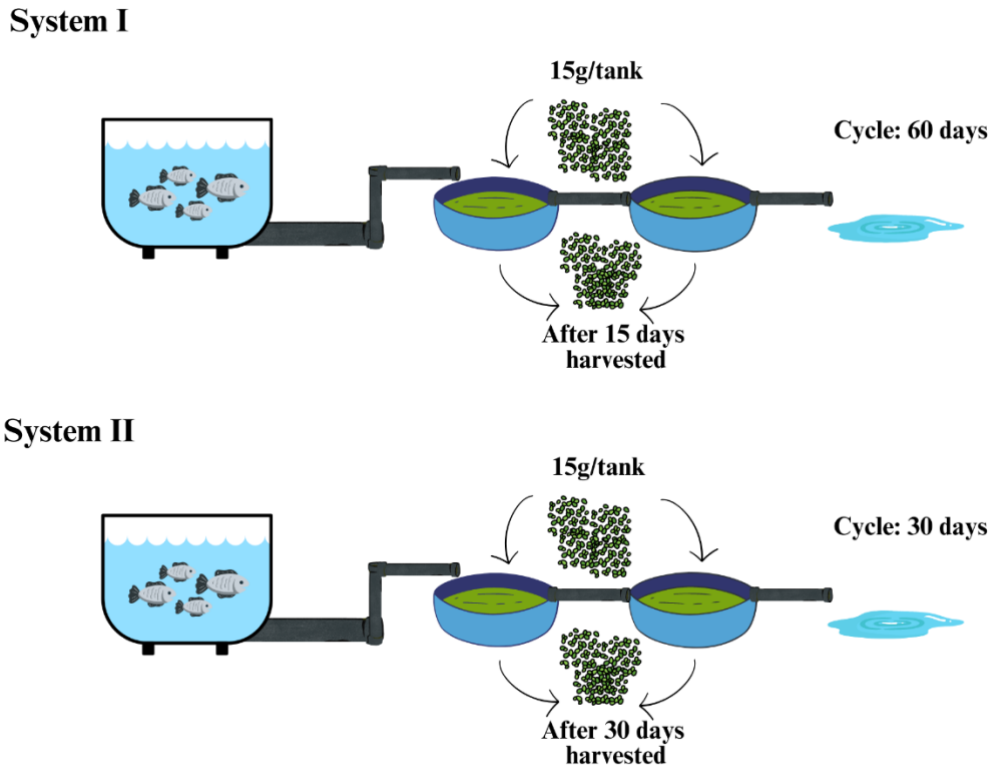


Figure 9. Decantation system. **A)** 15-day fresh biomass cultivation interval; **B)** 30-day fresh biomass cultivation interval.

System II – *L. minor* culture interval of 30 days

Each tank in the decantation system was seeded with 15 g of fresh *L. minor* biomass. Cultivation lasted 30 days during midsummer (from 12/21 to 01/21/2019). After 30 days, the total fresh biomass was harvested, and effluents were collected from the IMTA system for physical-chemical analysis (Figure 10).

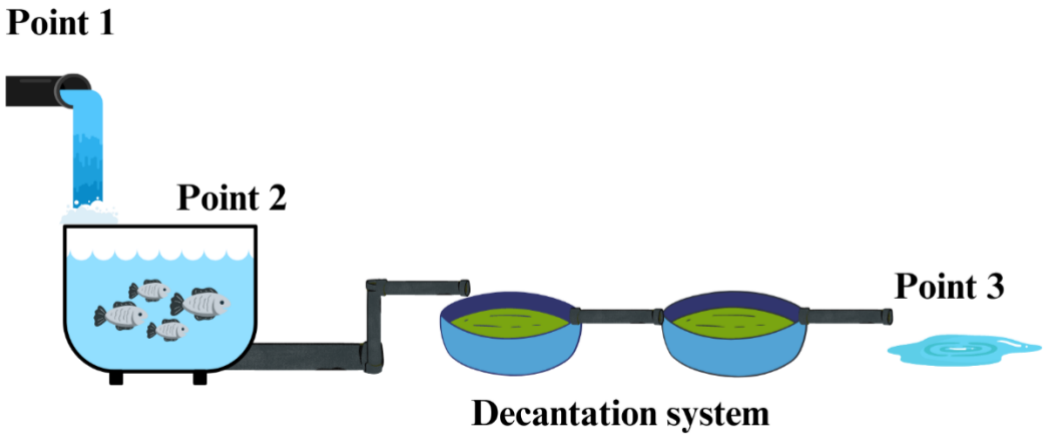


Figure 10. Collection of effluent in the IMTA system: Point 1) Capture water; Point 2) Effluent from the fish production system; Point 3) Effluent from the decantation system.

2.2.2. Bioremediation in a batch system

The liquid effluent from fish production was collected in 50 L plastic tanks and transported to the São Paulo State University, Registro Campus. In a climate-controlled laboratory, a completely randomized experiment was conducted in triplicate to test the effectiveness of a decantation system in treating effluent. The control group consisted of a rectangular 25 L polyethylene tank filled with liquid effluent from fish production.

The treatment group used a rectangular polyethylene tank with a 25 L capacity and 0.15 m² of water surface area to grow *L. minor*. Initially, 100 g of fresh *L. minor* biomass was added to each tank to cover the surface of the effluent, and the cultivation interval was 10 days. Physical-chemical parameters, including pH, dissolved oxygen, nitrate, and ammonia levels, were analyzed every two days. At the end of the cultivation period, the total fresh biomass in the system was harvested using a net and a sieve and weighed.

2.3. Evaluation of the Trophic State Index

At the laboratory, samples of inlet water, effluent from the fish production system, and effluent from the decantation system were filtered using a vacuum filtration system with a pump and a 0.4 µm glass fiber filter to extract the existing plankton in the production system. The filtered samples were subsequently frozen for analysis. Chlorophyll levels were used to indicate the plankton's degree of fixation in the production system. They were determined by spectrophotometry using a cuvette with

1 cm of optical path in a Shimadzu® UV-1800 spectrophotometer. Concentrations were determined according to the literature presented by Jeffrey & Humphrey (1975) (Table 1).

Table 1. Equations used to quantify chlorophylls, total carotenoids and astaxanthin concentrations (mg.g^{-1}) (Jeffrey & Humphrey, 1975; Lorenze & Jeffrey, 1980; Koopmann et al., 2022).

Pigment	Equation
Chlorophyll a (Cla)	Cl*a* = 12.25 A_{664} – 2.79 A_{647}
Chlorophyll b(Clb)	Cb = 21.50 A_{647} – 5.10 A_{664}
Total Carotenoids (TC)	TC = (1000 A_{470} – 1.90Cla – 63.14 Cb)/214
Astaxanthin (As)	As = 0.8*TC A_{468}

A_{664} = Absorbance value at a wavelength of 664nm; A_{647} = Absorbance value at a wavelength of 647nm; A_{470} = Absorbance value at a wavelength of 470nm; A_{468} = Absorbance value at a wavelength of 468nm; A_{454} = Absorbance value at a wavelength of 454nm.

The Trophic State Index (TSI), according to Lamparelli (2004), was calculated using the results obtained. The TSI comprises two indices, the Trophic State Index for Chlorophyll a – TSI (CL) (Equation 1) and the Trophic State Index for Phosphorus – TSI (PT) (Equation 2), both established for lotic environments. Equation 3 was used to obtain the TSI, the simple arithmetic mean of TSI (CL) and TSI (PT) calculated from the Total Phosphorus and Chlorophyll results.

$$TSI(Cla) = 10.\left[6 - \left[\frac{0{,}92 - 0{,}34.(\ln(Cla))}{ln\ 2}\right]\right] \quad (1)$$

$$TSI\ (TP) = 10.\left[6 - \frac{1{,}77 - 0{,}42.(ln\ (TP))}{ln\ 2}\right] \quad (2)$$

$$TSI = \frac{[TSI\ (TP) + IET(CL)]}{2} \quad (3)$$

Where: Cla: Chlorophyll concentration measured at the water surface, in µg.L^{-1}; TP: Total Phosphorus concentration measured at the water surface, in µg.L^{-1}; TSI: Trophic State Index.

The results obtained in the Trophic State Index calculations were compared with the classifications of lotic environments described by Lamparelli (2004) (Table 2).

Table 2. Trophic State Index (TSI) classification for different water concentration levels.

Trophic Level	TSI
Ultraoligotrophic	TSI ≤ 47
Oligotrophic	47 < TSI ≤ 52
Mesotrophic	52 < TSI ≤ 59
Eutrophic	59 < TSI ≤ 63
Super eutrophic	63 < TSI ≤ 67
Hypereutrophic	TSI > 67

2.4. Variables analyzed in bioremediation and the Trophic State Index

2.4.1. Physicochemical analysis

Physical-chemical analyses were conducted in both the IMTA system and the batch system at three different points: the inlet water (Point 1), effluent from the fish production system (Point 2), and effluent from the decantation system (Point 3) (Figure 2). The physical parameters of the water were measured on-site using the Multiparameter Meter - Asko® ASK88, which determined the temperature (ºC), pH, dissolved oxygen (OD), and electrical conductivity (EC). Afterward, water was collected from the points and stored in 900 ml plastic bottles at 5 ºC during transportation to the laboratory in a thermal box. The chemical parameters of the water were analyzed using the Waterproof Multiparameter Meter - Asko® Micro 20, which determined the levels of ammonia (NH_3), nitrite (NO_2), nitrate (NO_{3-}), and phosphate (PO_4^{3-}).

2.4.2. Efficiency of removal of nitrogenous compounds

The effluent from fish farming underwent a biological treatment process utilizing *L. minor* in the IMTA system. The percentage of nitrogenous compounds removed was determined for the continuous flow systems (system I and system II) and the batch system (Equation 4) to evaluate the system's efficiency.

$$\eta = \frac{Ie - Fe}{Ie} \text{x}100 \quad (4)$$

Where: η: Nitrogen compounds removal efficiency; Ie: Concentration of nitrogenous compounds in the initial effluent; Fe: Concentration of nitrogen compounds in the final effluent.

2.4.3. Determination of relative growth rate of fresh biomass

The relative growth rate (RGR) of *L. minor* was assessed in both the decantation system with continuous flow and the batch system by calculating the ratio of the variation of the fresh biomass (Equation 5).

$$RGR = \frac{\ln \text{final weight} - \ln \text{initial weight}}{\text{final time} - \text{initial timel}} x100 \quad (5)$$

2.4.4. Evaluation of the production area of fresh biomass of L. minor necessary to remove total phosphorus from the effluent

To assess the efficiency of *L. minor* in removing P from the effluent generated in conventional fish production, it was essential to determine the minimum area of fresh biomass production of *L. minor* in the IMTA system. The total P output (in kg) of the conventional system was calculated by multiplying the phosphorus concentration in the effluent (in g/L) and the output flow (in m³/year) for the 12-month fish production cycle. The amount of P absorbed by the fresh biomass of *L. minor* per unit area (in g/m²) was determined by multiplying the phosphorus content in dry biomass (in g/kg) and the amount of fresh biomass produced during the fish production cycle (in kg/m²). The required area (m²) of fresh biomass production of *L. minor* to remove the total phosphorus generated in the fish production effluent was then calculated by dividing the total phosphorus output in the effluent by the total phosphorus in the fresh biomass production of *L. minor*.

2.5. Quality of dry biomass of L. minor

2.5.1. Minimum viable processing of fresh biomass

The total harvest of fresh biomass of *L. minor* produced in the IMTA and batch systems was transported to the Food Technology Laboratory at the São Paulo State University, Registro Campus. The biomass underwent minimum viable processing to obtain *L. minor* flour for quality analysis. The processing steps included washing the fresh biomass with running water through a sieve until the water ran clear and transparent. Then, 1 kg of the fresh biomass was added to each stainless-steel tray (47 x 59 cm) and dried for 24 hours at 45 ºC in an oven with circulation and air renewal (Teknal®).

The dried biomass was then ground into an *L. minor* flour using a domestic grain processor (Philips Wallita®). Finally, the *L. minor* flour was sealed and vacuum packed in transparent airtight bags using industrial vacuum equipment (R.Baião®) and stored at room temperature.

2.5.2. Crude protein and amino acids profile

The Kjeldahl method (1883) was used to determine the percentage of crude protein (CP) in dry biomass of *L. minor*. This method multiplied the total nitrogen value in the nitrogen analysis by the conversion factor 6.25, commonly used for forage plants and concentrated feed.

Amino acids profile was quantitative determinate by high-performance liquid chromatography (HPLC), where the individualization was initially carried out of monomers through hydrolysis by HCl 6N at 110 °C for 24 hours (White et al., 1986; Appenroth et al., 2017).

2.5.3. Lipids and fatty acids profile

The extraction and quantification of total lipids followed the method of Bligh & Dyer (1959). Initially, the dry biomass was macerated and suspended in a PBS buffer. Subsequently, 5 mg/mL of tritridecanoin in hexane and 12.5 mL of chloroform, methanol, and water (2, 2, 1) were added. After centrifugation, the chloroform layer was collected and dried under an N_2 atmosphere to determine the gravimetric content of total lipids. To convert fatty acids to fatty acid methyl esters (FAME), the dry lipids extract was dissolved in 500 µL of 5% HCl in methanol, and the mixture was incubated for 2 hours at 100 °C. After cooling, 1.25 mL of water and 1.25 mL of hexane were added to extract the FAME.

The FAME was analyzed by gas chromatography coupled to a mass spectrometer (GCEM) on a fused silica capillary column (VF-Wax, with dimensions of 30 m, 0.25 nm, 0.25 µm film thickness, Agilent). The injection temperature was set at 220 °C with a 1 µL volume in Split mode. Helium was used as a carrier gas with a flow rate of 1 $mL.min^{-1}$, and the temperature ramped from an initial temperature of 60 °C to 260 °C at a rate of 5 °C per min, held for 10 minutes. The Supelco 37 standard was used to identify peaks and fatty acids by comparing retention times with standards and mass spectra from the NIST library. FAME that did not meet a similarity index of 90%

was not considered. Most FAME was quantified using the standard curve equation for the respective FAME from the Supelco 37 standard.

2.5.4. Mineral macro and micronutrients

The dry biomass samples were analyzed for micronutrients and macronutrients at the Laboratory of Soil Fertility and Plant Nutrition (LAFEN) at the São Paulo State University in Registro. The micronutrients (B, Cu, Fe, Mn, and Zn) and macronutrients (N, P, K, Ca, Mg, and S) were determined. N by the Kjeldahl method (1883) (Galvani & Gaertner, 2006), P by colorimetry, S by barium sulfate turbidimetry, B by Azomethine-H and K, Ca, Mg, Cu, Fe, Mn, and Zn in an atomic absorption spectrophotometer, after nitric-perchloric digestion as proposed by Malavolta et al., (1997). The results were expressed in g content of the element per kg of dry biomass of *L. minor* ($g.kg^{-1}$).

2.5.5. Determination of mineral micro and macronutrients

To extract and quantify photosynthetic pigments, 0.002 g of crushed dry biomass of *L. minor* was homogenized in a 90% acetone solution and placed in 1.5 ml microtubes. The samples were centrifuged at 100 rpm for 10 minutes at 4 °C in a refrigerated microtube centrifuge (Hitachi®) and kept in the dark for 1 hour.

Concentrations were determined according to wavelengths and equations to the literature presented by Jeffrey & Humphrey (1975), Lichtenthaler (1987) for total carotenoids and by Lorenze and Jeffrey (1980) for astaxanthin (Koopmann et al., 2022) (Table 1).

3. RESULTS AND DISCUSSION

3.1. Evaluation of bioremediation

The results of bioremediation demonstrated that *L. minor* was efficient in bioremediation in System II, substantially reducing NH_4, NO_3, and PO_4. The physical quality of the effluent in the decantation System I at Point 3 (effluent from decantation) fails to meet the minimum parameters required for the species to grow, as indicated in Table 3.

This is due to the growth of fresh biomass of *L. minor* being dependent on various limiting factors, such as temperature, pH, nitrogen, and phosphorus (Oliveira,

2013; Leng, 1999). According to Oliveira (2013), temperatures between 20 - 31 ºC are recommended for optimal growth. Conversely, at temperatures below 5 ºC, *L. minor* ceases growth, resulting in species mortality. However, although the species tolerates low temperatures, it was observed that below 20 ºC metabolism decreases, decelerating growth in System I (Table 3).

Table 3. Mean values of the physical-chemical parameters of the effluents analyzed in the IMTA system – System I.

Point	OD ($mg.L^{-1}$)	T (ºC)	EC (µS)	pH	NH_4 ($mg.L^{-1}$)	NO_3 ($mg.L^{-1}$)	PO_4 ($mg.L^{-1}$)
1	7.07	15.93	26.15	6.16	0.01	2.05	0.03
2	5.30	16.40	44.63	6.52	0.04	8.43	2.43
3	5.00	12.85	44.39	9.93	0.06	5.60	5.54

Point 1: Capture water; Point 2: Effluent from the fish production system; Point 3: Effluent from the decantation system; Dissolved Oxygen (DO); Temperature (T); Electrical Conductivity (EC); Hydrogenionic Potential (pH), Total ammonia nitrogen (NH_4), Dissolved Nitrate (NO_3); Phosphate (PO_4).

Another limiting factor to growth is the pH; duckweed survives between 3.5 and 10.5. However, growth rates are best in the range of 6.5 - 7.5 (Oliveira, 2013; Leng, 1999). Our results showed that in the ideal pH range, ammonia is mainly present as the ammonium ion, the form of N most easily absorbed by *L. minor,* as observed in System II (Table 4). On the other hand, a high pH results in ammonia in a solution that can be toxic and can also be lost by volatilization (Leng, 1999).

The nitrogen concentration was higher than phosphorus in System I, Point 2 (effluent from fish production) (Table 3). The bioremediation of the effluent in the decantation system was directly influenced by several factors, including the temperature below 17 ºC and pH 6.23 and a culture interval of 15 days for *L. minor* (Table 3). Throughout the 60 days, the relative growth rate (RGR) remained stable at around 22% per day, and the accumulated fresh biomass increased by 114 times compared to the initial biomass of 15 g (Figure 3). Despite this, there was no significant removal of ammoniacal nitrogen (-20.83%) or phosphate (-281.77%) after bioremediation in the decantation system. Additionally, a low reduction of nitrate (31.61%) was observed in the effluent of the decantation system.

In System II Point 2 (effluent from fish production), nitrogen concentration was lower than phosphorus, and the results of bioremediation of the effluent in the

decantation system were influenced by the 30 days of cultivation, temperature (29.2°C), and pH (6.56) (Table 4). There was a gradual increase in the relative growth rate (RGR) of fresh biomass, and after 30 days, the RGR was 98%.day^{-1}. The increase in accumulated fresh biomass was 126 times greater than the initial biomass after 30 days (Figure 3). These factors contributed to removing nitrogenous compounds from the effluent NH_4 96.71%, NO_3 87.47%, and PO_4 97.18%, occurring bioremediation in the decantation system.

In Batch System, the nitrogen concentration was higher than that of phosphorus, as observed in System I. However, the temperature (18.30 - 22.10 ºC) remained within the adequate range for the biomass production of the species. Remarkably, the system significantly reduced nitrogen and phosphorus concentration in just six days, with an initial biomass input of 100 g and a volume of 25 L. Despite a transient increase in the concentration of phosphorus from the 8th to the 10th day, there was a significant removal of nitrogenous compounds, including NH_4 (100%), NO_3 (93.15%), and PO_4 (87.81%), with bioremediation occurring. Additionally, fresh biomass's relative growth rate (RGR) was 9% per day, and the increase in biomass was six times greater than the initial biomass after 10 days (Figure 11).

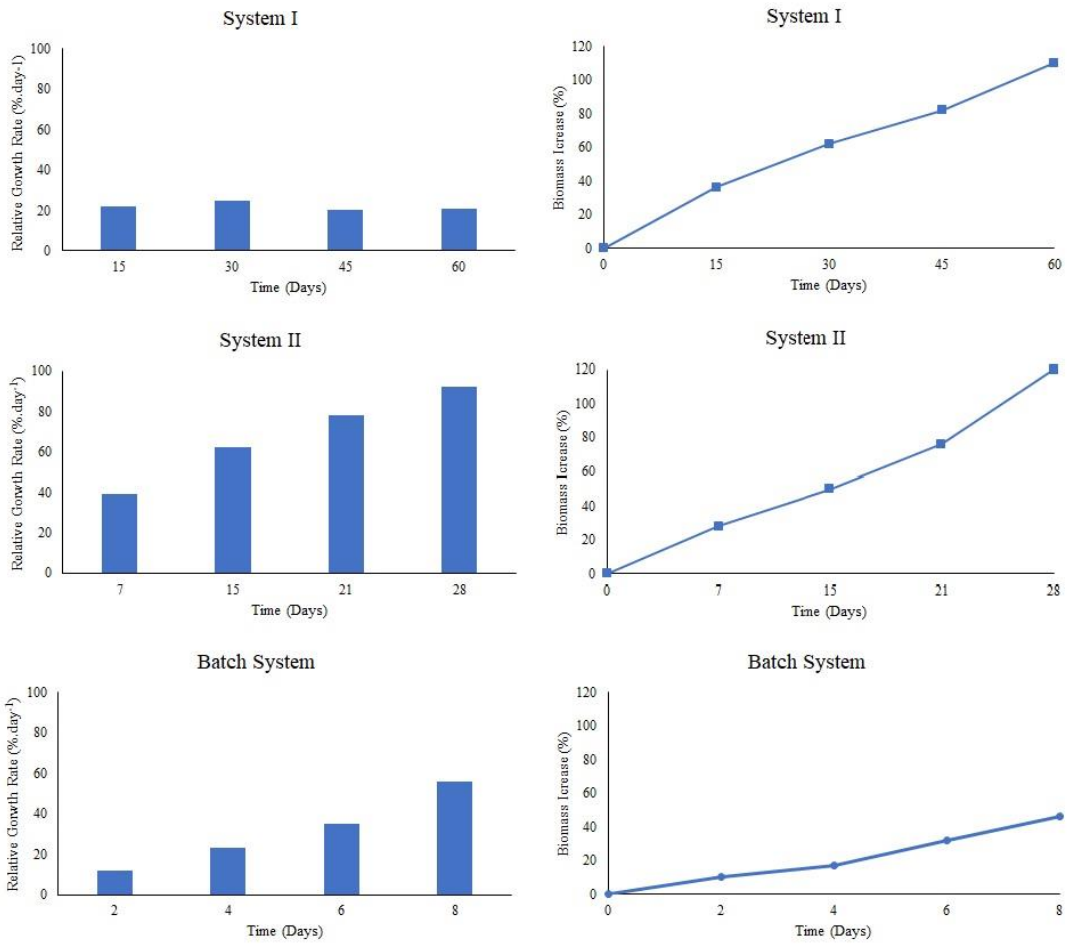


Figure 11. (I) Growth rate (%.day^{-1}) and (II) increase in accumulated fresh biomass (%) of *L. minor* in continuous flow – System I, System II and Batch System.

Other studies show the efficiency of bioremediation of aquaculture effluents, such as the use of *L. valvidiana* for the removal of nitrogenous compounds from the effluent from the production of *Oreochromis niloticus* in a circular tank of 1m² in area and volume of 310 L (Mohedano, 2004). In this study, in just 14 days, bioremediation was achieved. Cerqueira (2021) used *Landoltia punctata* for the removal of nitrogenous compounds from the effluent generated by the production of *O. niloticus* and obtained the bioremediation in 42 days in a circular tank of 1m² in area and volume of 500 L.

The concentration of nitrogen and phosphorus in the effluent is directly correlated to the growth of *L. minor* and in bioremediation (Leng, 1999). In the decantation system, *L. minor* can produce biomass if the effluent has a high phosphorus content. However, nitrogen concentrations need to be maintained, thus

removing nitrogenous compounds from the effluent (Leng et al., 1995), as observed in System II (Table 4).

Table 4. Mean values of the physical-chemical parameters of the effluents analyzed in the IMTA system – System II.

Point	OD ($mg.L^{-1}$)	T (ºC)	EC (µS)	pH	NH_4 ($mg.L^{-1}$)	NO_3 ($mg.L^{-1}$)	PO_4 ($mg.L^{-1}$)
1	6.10	22.40	24.00	9.00	0.12	2.09	> 0.03
2	7.70	29.20	22.60	6.56	15.20	4.07	28.05
3	4.00	29.20	23.10	6.20	0.50	0.51	0.79

Point 1: Capture water; Point 2: Effluent from the fish production system; Point 3: Effluent from the decantation system; Dissolved Oxygen (DO); Temperature (T); Electrical Conductivity (EC); Hydrogenionic Potential (pH); Total ammoniacal nitrogen (NH_4); Dissolved Nitrate (NO_3) and Phosphate (PO_4).

Suppose the effluent contains more nitrogen than phosphorus. In that case, *L. minor* can remove the phosphorus in its biomass for metabolic activities, so the species will continue to grow in effluents with low phosphorus content (Leng et al., 1995). However, there is a low removal of nitrogenous compounds by the species, as observed in System I. In addition, phosphorus is highly soluble and released quickly into the environment, thus causing *L. minor* mortality and increased eutrophication in the aquatic environment (Leng et al., 1995).

3.2. Evaluation of the Trophic State Index (TSI)

For the study of the Trophic State Index, the indirect disposal of effluents was compare to CONAMA resolution nº 357/05 for class 2 rivers – pH (6.0 - 9.0); ammonia nitrogen (3.7 $mg.L^{-1}$ N, for pH ≤ 7.5) (2.0 $mg.L^{-1}$ N, for 7.5 < pH ≤ 8.5) (1.0 $mg.L^{-1}$ N, for 8.0 < pH ≤ 8.5) (0.5 $mg.L^{-1}$ N, for pH > 8.5); nitrate 10.0 $mg.L^{-1}$; total phosphorus 0.1 $mg.L^{-1}$ (lotic environments and tributaries of intermediate environments).

The average of effluents from fish production in System I - Point 2 presented pH (6.52), ammoniacal nitrogen (0.04 $mg.L^{-1}$), and nitrate (8.43 $mg.L^{-1}$) within the limits required by CONAMA. However, the phosphate result (2.43 $mg.L^{-1}$) obtained the result above the limit required by legislation (Table 5).The average of the effluents from the decantation system - Point 3, presented ammoniacal nitrogen (0.06 $mg.L^{-1}$) and nitrate (5.60 $mg.L^{-1}$) within limits required by CONAMA Resolution nº 357/05. However, the

pH (9.43) and phosphate (5.54 $mg.L^{-1}$) results were above the limit required by law (Table 5).

Table 5. Comparison of effluent quality in System I according to CONAMA resolution nº 357/05.

Points	pH	NH_4 ($mg.L^{-1}$)	NO_3 ($mg.L^{-1}$)	PO_4 ($mg.L^{-1}$)
1	6.16	0.01	2.05	0.03
2	6.52	0.04	8.43	2.43
3	9.43	0.06	5.60	5.54
CONAMA	6.00 -9.00	0.50 – 3.70	10	0.10

Point 1: Capture water; Point 2: Effluent from the fish production system; Point 3: Effluent from the decantation system; CONAMA Resolution 357/05 - NO_3: 0.5 $mg.L^{-1}$ N, for pH > 8.5 and 3.7 $mg.L^{-1}$ N, for pH ≤ 7.5.

The effluents from fish production – Point 2 and from the decantation system – Point 3 (Table 6) presented a trophic degree classified as mesotrophic (52 < IET ≤ 59) and eutrophic (59 < IET ≤ 63), with the mean classified as eutrophic (59 < EIT ≤ 63).

Table 6. Mean trophic state index and trophic degree in IMTA system after bioremediation in System I.

FU	Collection points		
	1	2	3
A	34	63	63
B	40	59	59
C	36	61	58
Mean	37	61	60

FU: Family Unit; Point 1: Capture water; Point 2: Effluent from the fish production system; Point 3: Effluent from the decantation system.

3.2.2. TSI – System II

The average of effluents from fish production – Point 2, presented pH (6.56) and nitrate (4.07 $mg.L^{-1}$) within the limits required by CONAMA Resolution nº 357/05. Ammoniacal nitrogen (15.2 $mg.L^{-1}$) and phosphate (25.05$mg.L^{-1}$) had results above the limit required by the resolution (Table 7). The average of the effluents from the decantation system - Point 3, presented pH (6.20), ammoniacal nitrogen (0.51 $mg.L^{-1}$) within limits required by CONAMA Resolution nº 357/05 but did not obtain a minimum result of phosphate (0.79 $mg.L^{-1}$) required by law (Table 7).

Table 7. Comparison of effluent quality in System II according to CONAMA resolution nº 357/05.

Points	pH	NH_4 ($mg.L^{-1}$)	NO_3 ($mg.L^{-1}$)	PO_4 ($mg.L^{-1}$)
1	9.00	0.12	2.09	>0.03
2	6.56	15.2	4.07	25.05
3	6.20	0.51	0.51	0.79
CONAMA	6.00 -9.00	0.50 – 3.70	10	0.10

Point 1: Capture water; Point 2: Effluent from the fish production system; Point 3: Effluent from the decantation system; CONAMA Resolution 357/05 - NO_3: 3.7 $mg.L^{-1}$ N, for pH ≤ 7.5.

Fish production effluents – Point 2 (Table 8) presented a trophic degree classified as supereutrophic (63 < IET ≤ 67), with the average classified as supereutrophic (63 < IET ≤ 67). The effluents from the decantation system – P3 presented the degree of trophic classified as mesotrophic (52 < IET ≤ 59), with the mean classified as oligotrophic (47 < IET ≤ 52).

Table 8. Mean trophic state index and trophic degree in IMTA system after bioremediation in System II.

FU	Collection points		
	1	2	3
A	34	65	51
B	40	65	51
C	36	64	48
Mean	37	65	50

FU: Family Unit; Point 1: Capture water; Point 2: Effluent from the fish production system; Point 3: Effluent from the decantation system.

3.2.3. TSI – Batch system

The final average on the 10th day in the control effluents showed pH (8.60), ammonia nitrogen (0.00 $mg.L^{-1}$), and nitrate (2.00 $mg.L^{-1}$) within the limits required by CONAMA Resolution No. 357/05 (Table 9). However, it did not obtain the minimum phosphate result (4.20 $mg.L^{-1}$) required by law. At the end of the experiment, the control presented the trophic degree classified as mesotrophic (52 < IET ≤ 59) (Table 10). The final average on the 10th day in the treatment effluents showed pH (7.20), ammonia nitrogen (0.00 $mg.L^{-1}$), and nitrate (2.54 $mg.L^{-1}$) within limits required by CONAMA Resolution No. 357/05. However, it did not obtain the minimum phosphate result (0.78 $mg.L^{-1}$) required by law (Table 9).

Table 9. Mean values of physical-chemical parameters of the effluents analyzed after bioremediation in a batch system.

Systems	Days	OD ($mg.L^{-1}$)	T (ºC)	EC (µS)	pH	NH_4 ($mg.L^{-1}$)	NO_3 ($mg.L^{-1}$)	PO_4 ($mg.L^{-1}$)
Control	2	4.53	28.97	47.13	7.14	0.13	37.10	6.40
	4	4.40	20.20	46.97	7.10	0.00	16.70	1.15
	6	5.00	18.30	47.27	7.46	0.00	12.60	1.21
	8	4.90	20.40	48.60	8.10	0.00	1.52	3.80
	10	4.80	22.10	4.8	8.60	0.00	2.00	4.20
Treatment	2	4.53	18.70	44.93	5.73	0.02	10.20	0.55
	4	4.10	20.00	49.03	6.62	0.00	6.60	0.35
	6	4.53	18.30	49.53	6.71	0.00	4.19	0.35
	8	4.80	20.70	48.30	7.60	0.00	2.45	0.92
	10	4.10	22.10	65.70	7.20	0.00	2.54	0.78

Control: Effluent from the fish production system without L. minor; Treatment: Effluent from the fish production system with *L. minor*; Dissolved Oxygen (DO); Temperature (T); Electrical Conductivity (EC); Hydrogenionic Potential (pH); Total ammoniacal nitrogen (NH_4); Dissolved Nitrate (NO_3) and Phosphate (PO_4).

The degree of trophy in the control effluent was classified as mesotrophic (52 < IET ≤ 59), and from the second day of treatment of the effluent with *L. minor*, the degree of trophicity changed to oligotrophic (47 < EIT ≤ 52) (Table 10). The efficiency in reducing the trophic degree of the IMTA system in the effluent generated in the production of *C. gariepinus* is directly correlated with the ability of *L. minor* to remove nitrogenous compounds from the fish production system in continuous flow and the cultivation interval of the macrophyte in the bioremediation system (Walsh et al., 2021).

Table 10. Mean trophic state index and trophic degree after bioremediation in a batch system.

Days	Control	Treatment
2	58	50
4	53	48
6	53	49
8	57	51
10	57	51
Mean	56	50

Control: Effluent from the fish production system without *L. minor*; Treatment: Effluent from the fish production system with *L. minor*.

In system I, where the *L. minor* cultivation interval was 15 days, there was a low removal of nitrogenous compounds. For this reason, the average trophic degree of the effluent continued as eutrophic, with the same classification in the conventional system and of the IMTA system. In system II, where the *L. minor* cultivation interval was 30 days, nitrogenous compounds were removed, ranging from 87.47% to 97.18%. The ability of *L. minor* to remove nutrients in the effluent from the IMTA system proved efficient. The mean trophic degree classified as supereutrophic in the conventional system changed to oligotrophic in the IMTA system. However, the average phosphate in the IMTA system was above the limit CONAMA Resolution 357/15 allowed.

3.2.4. Evaluation of the production area of fresh biomass of L. minor necessary to remove total phosphorus from the effluent

Our results suggested that the potential for removal of nitrogenous compounds of the *L. minor* in the decantation system in continuous flow depends directly on the area (m²) used to produce fresh biomass of the macrophyte. In this way, in the constant flow system - System I and System II, it was observed that to remove the amount of 70.9 kg of phosphorus generated in the effluent of the conventional *C. gariepinus* system during 12 months of production, it would be necessary to produce 3,166.00 m² of water depth with *L. minor.* This occurred once the species of *C. gariepinus* was produced in 20 m³ elevated tanks that used 2,365.2 $m^3.year^{-1}$ of water in a continuous

flow system. Thus, after the 30 days residence period of the macrophyte with the surface completely covered in the IMTA system, *L. minor* would remove 100% of the phosphate generated during the fish production cycle.

On the other hand, to effectively remove 0.6 kg of phosphorus from a 20 m² batch system effluent using *L. minor*, a water depth of 26.77 m² would be required. This depth can be achieved by growing *L. minor* to cover the entire surface area of the IMTA. With a culture interval of 10 days, *L. minor* can remove 100% of the phosphate generated during the fish production cycle. This demonstrates the effectiveness of *L. minor* in reducing the nutrient load in the system, thereby promoting a healthier and more sustainable aquatic environment corroborating with the 4R strategies: reduce, reuse, recycle, and recover (Liaros, 2021). According to Liaros (2021), a food system that eliminates pollution waste and regenerates natural systems can be described as a circular food economy. In this way, the results of the effectiveness of *L. minor* contribute to the circular economy and a sustainable future in aquaculture.

3.3. Chemical composition of dry biomass of L. minor

3.3.1. Crude protein and amino acids profile

Crude protein (CP) content in dry biomass of *L. minor* was higher than 30% in both systems, evidencing the potential use of duckweed as a protein source for human consumption, particularly in developing countries where protein deficiency is a significant health issue (Xu et al., 2022). In System I, the CP content was 36% in the cultivation interval of 15 days. While in System II, where the *L. minor* cultivation interval was 30 days, was obtained 35% of the CP (Figure 12).

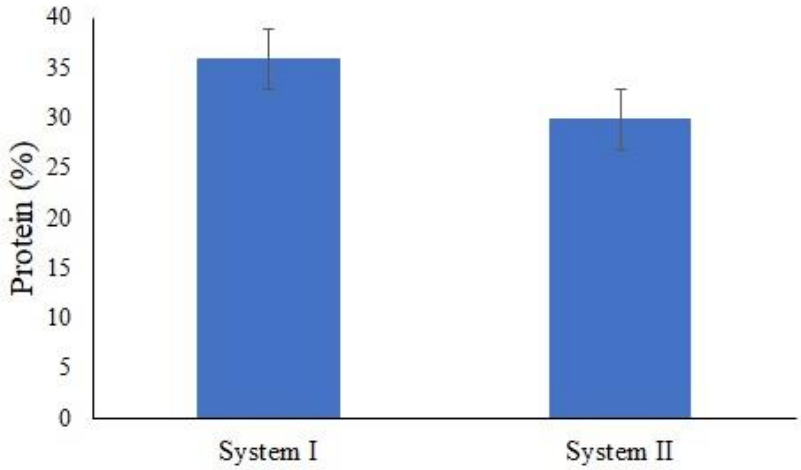


Figure 12. Mean protein (%) in the dry biomass of *L. minor* in the continuous flow settling system).

The growth of *L. minor* varies according to the amount of nitrogen and phosphorus present in the effluent. However, the composition of ammonia is paramount in the effluent, as the synthesis of proteins in the macrophyte is produced directly through the absorption of ammonia by the aquatic plant (Oron et al., 1988). These variations in crude protein were observed in other studies. Mohedano (2004) found 31.78% CP in the dry biomass of *L. valvidiana* grown in aquaculture effluent. Graeff et al. (2007) verified 45% of CP in *L. minor* collected in the pond of a rural property. In *Lemna sp*., values between 20 and 35% CP were observed in plants grown in the Schenk-Hildebrandt nutrient medium (Appenroth et al., 2017). Also, in *Lemna sp.*, 39.55% CP was found after 7 days of cultivation in swine effluent and a decrease in nutrients and protein content after 14 and 21 days (Tavares, 2004). Chakrabarti et al. (2018) verified 36.07% and 27.12% of the protein in the dry biomass of *L. minor* grown in water fertilized with organic and inorganic fertilizers.

In this way, due to the duckweed having a high crude protein content, ranging between 20 - 45% on a dry weight basis, the species is comparable to other plant-based sources of protein such as soybeans and peas (Kaplan et al., 2019; Xu et al., 2022). Thus, the plant is a viable alternative to traditional protein sources, which may offer cost, sustainability, and nutritional value advantages.

The high protein values observed are accompanied by an interesting amino acid profile, meeting the recommendations of the world health organization (Table 11).

Table 11. Amino acid composition of proteins from *Lemna* species [g/ 100 g protein]. Comparison between biomass produced in our IMTA system and grown in Schenk-Hildebrandt medium (Appenroth et al., 2018; Pagliuso et al., 2022).

Amino acid content g/100g protein			
Essentials amino acids			
	This study	Appenroth et al., 2018	Pagliuso et al., 2022
Alanine	5,4	5,1	8,4*
Histidine	1,6	1,5	0.9
Isoleucine	4,2	3,7	1.1
Leucine	7,6	7,3	1.1
Lysine	4,9	5	2.9
Methionine	1,3	1,6	2.4
Phenylalanine	4,7	4,4	1.1
Threonine	5,0	4	0.9
Valine	5,2	4,6	3.5
Tryptophan	1,3	NR	1.2
Non-Essentials amino acids			
Arginine	5,3	4,8	7.5
Asparagine	8,1	8,2	23.9
Cysteine	0,8	0,9	4.4
Glutamine	9,4	9,8	14.0
Glycine	4,9	4,6	0.7
Proline	4,5	3,8	NR
Serine	3,9	4,1	2.2
Tyrosine	2,9	3,1	*

NR - Not Rated; * in Pagliuso et al., 2022 were presented Alanine + Tyrosine.

The qualitative and quantitative evaluation values indicate that duckweed produced at IMTA has similar values to biomass from controlled production systems using artificial culture media (Appenroth et al., 2017; Pagliuso et al., 2022). Consumption of essential amino acids promotes benefits for both cognitive (Suzuki et al., 2020) and physical and physiological performance (Jang et al., 2022). According to these studies, the levels of isoleucine (10%), valine (12%), threonine (12%), and

tryptophan (3%) available in the biomass produced in IMTA can be classified as a source of these amino acids.

3.3.2. Lipids and fatty acids

The dry biomass of *L. minor* produced in the IMTA system represents a potential source of raw materials for fatty acids to be used in animal nutrition. It was obtained 92.32 ± 21.74 $mg.g^{-1}$ of total lipids in dry biomass. The chemical composition of fatty acids was dominated by saturated fatty acids (SFA), which represented 43.67% of the total fatty acids, mainly palmitic acid (18:1n9) (28.01%), followed by polyunsaturated fatty acids (PUFA) (30.69%) and monounsaturated (MUFA) (26.24%) (Table 12).

Table 12. Composition of fatty acids in the dry biomass of *L. minor* in percentage and absolute (mg of FA g^{-1} of LT).

Fatty acids	Percentage	Absolute
Saturated (SFA)		
C6:0	0.31 ± 0.07	0.17 ± 0.03
C8:0	2.08 ± 1.87	1.11 ± 0.83
C10:0	1.98 ± 2.17	1.01 ± 0.89
C12:0	0.23 ± 0.08	0.14 ± 0.10
C13:0	2.37 ± 1.08	1.26 ± 0.21
C14:0	1.92 ± 0.50	1.17 ± 0.62
C15:0	0.97 ± 0.15	0.58 ± 0.27
C16:0	28.01 ± 4.80	15.83 ± 3.54
C17:0	0.61 ± 0.07	0.35 ± 0.08
C18:0	2.32 ± 0.67	1.30 ± 0.36
C20:0	0.52 ± 0.12	0.29 ± 0.04
C22:0	0.67 ± 0.18	0.37 ± 0.03
C23:0	0.37 ± 0.01	0.20 ± 0.01
C24:0	1.57 ± 0.82	0.80 ± 0.23
Monounsaturated (MUFA)		
C14:1	1.60 ± 0.01	1.29 ± 0.01
C15:1	0.22 ± 0.01	0.18 ± 0.01
C16:1	7.21 ± 6.73	5.08 ± 6.10

C17:1	0.40 ± 0.01	0.32 ± 0.01
C18:1n9c	2.21 ± 0.89	1.41 ± 1.04
C18:1n9t	16.08 ± 3.56	8.91 ± 1.21
Polyunsaturated (PUFA)		
C18:2n6c (LA)	10.84 ± 2.07	6.28 ± 2.10
C18:2n6t	3.91 ± 2.90	1.98 ± 1.74
C18:3n3 (LNA)	15.66 ± 3.42	9.57 ± 5.49
C18:3n6 (GLA)	0.62 ± 0.01	0.50 ± 0.01
C20:3n3 (ETE)	1.05 ± 0.01	0.85 ± 0.01
C20:4n6 (AA)	0.72 ± 0.01	0.59 ± 0.01
C20:5n3 (EPA)	0.57 ± 0.01	0.46 ± 0.01
Sums and ratios		
SFA	43.67 ± 7.74	24.44 ± 4.12
MUFA	26.24 ± 5.34	16.00 ± 8.97
PUFA	30.09 ± 3.82	17.97 ± 7.87
n-3	16.20 ± 4.35	10.01 ± 6.24
n-6	13.89 ± 4.59	7.96 ± 2.97
n-6/n-3	1.78 ± 1.04	0.93 ± 0.48
PUFA/SFA	1.07 ± 0.11	0.63 ± 0.25
Total fatty acids		**58.41 ± 20.71**

NA: Not detected; SFA: sum of saturated fatty acids; MUFA: sum of monounsaturated fatty acids; PUFA: sum of polyunsaturated fatty acids; n-6: sum of omega-6 fatty acids; n-3: sum of omega-3 fatty acids; n-6/n-3: ratio of the sum of omega-6 fatty acids to the sum of omega-3 fatty acids; PUFA/SFA: ratio of the sum of PUFA and SFA.

PUFA from the omega-3 family represented 16.20% of the total fatty acids, with α-linolenic acid (18:3n-3, LNA) (15.66%) in the highest percentage, followed by PUFA from the omega-6 family (13.89%), the majority being linoleic acid (18:2n-6) (10.84%). The n-6/n-3 ratio was 0.93 ± 0.48 (mean ± standard deviation).

PUFA were identified in smaller amounts, with eicosatrienoic acid (20:3n-3, ETE) (1.05%), eicosapentaenoic acid (20:5n-3, EPA) (0.57%), γ-linolenic acid (18 :3n-6, GLA) (0.62%) and arachidonic (20:4n-6, AA) (0.72%). Long-chain fatty acids (PUFA) are essential for human food and animal nutrition (Garcia-Casal et al., 2013; Perini et al., 2010). Data from the dry biomass of *L. minor* cultivated in water fertilized with organic fertilizers demonstrated a dominance by PUFA with 60-63% of the total fatty

acids, being the omega-3, α-linolenic acid (LNA) (41-47%) and omega-6, linoleic acid (LA) (17–18%) (Chakrabarti et al., 2018). These values are higher than those observed in the IMTA system. Tang et al. (2015) verified a dominance of α-linolenic acid (LNA) in the total fatty acids in the biomass of *Landoltia punctata* (40.56%), *Lemna aequinoctialis* (45.46%), *Spirodela polyrhiza* (46.09%), *Wolffia globosa* (49.78%) grown in nutrient medium - Schenk and Hildebrandt (S6765; Sigma).

The ratio of n-6/n-3 fatty acids was 0.25:1 in *S. polyrhiza* and 0.61:1 in W*. microscopic* (Appenronth et al., 2017); 0.3:1 in *L. minor* (Gading, 2019), 0.36:1 in *L. minor* (Chakrabarti et al., 2018). The n-6/n-3 ratio is essential for human nutrition, and the n6/n3 ratio should not exceed 5:1 (Appenronth et al., 2017; FAO, 2010; Perini et al., 2010).

In the duckweed produced in the IMTA system, a dominance by SFA (saturated AG) was observed, while AG, LNA, and LA are below those described by the authors above. However, the n-6/n-3 ratio was 0.93:1, indicating the beneficial potential for human food. In the West, the n-6/n-3 ratio ranges from 25:1 - 50:1 in the diet (Martin et al., 2006; Perini et al., 2010). An n-6/n-3 correlation ranging from 0:1 - 1:1 is highly beneficial for human health (Appenronth et al., 2017; FAO, 2010; Martin et al., 2006; Perini et al., 2010).

Some research also demonstrates the factors of this ratio in the n-6/n-3 patterns in human food. The lower the n-6/n-3 correlation, the lower the probability of chronic, inflammatory, and autoimmune diseases in humans (Appenroth et al., 2017; Martin et al., 2006; Perini et al., 2010). Freshwater fish do not need HUFA-type fatty acids. However, they require α-linolenic acid (18:3n-3, LNA) in the diet with concentrations of 0.5% to 1.5% (Gao et al., 2011). This fact is important when considering a diet rich in PUFA from the n-3 family since the formation of double bonds in HUFA, EPA, and DHA are stored as a source of energy to sustain growth and help in the metabolic process (Gao et al., 2011; Herawati et al., 2020). Thus, dry biomass of *L. minor* produced in the IMTA system has the potential as a sustainable and cost-effective source of SFA, MUFA, and PUFA-rich biomass for use in various applications such as functional foods, nutraceuticals, and animal feed.

3.3.3. Minerals

Our results showed that *L. minor*, produced in the IMTA, has the potential as a raw material or direct source, especially of iron, calcium, and magnesium for human food. Our study suggested that duckweed could be a promising food source that can be used as an ingredient in various food products such as bread, pasta, and snacks. Thus, the plant is highly nutritious and can be considered a potential food source for human consumption due to its high protein and nutritional value (Beukelaar et al., 2019).

It was observed that the dry biomass of *L. minor* showed a higher amount of nitrogen (N) (56.00 $g.kg^{1}$) and a lower amount of magnesium (Mg) (3.87 $g.kg^{-1}$) (Table 13). For micronutrients, a higher iron (Fe) content (323 $mg.kg^{-1}$) and a lower copper (Cu) content (8.40 $mg.kg^{-1}$) were found (Table 13). The Mg/Ca ratio was 0.31, and K/Na was not evaluated.

Table 13. Mean macro and micronutrients in the dry biomass of *L. minor*, *W. microscopic*, and *Wolffia sp*.

Macronutrients ($g.kg^{-1}$)	*L. minor*	*W. microscópica*	*Wolffia sp.*
N	56.00	43.20	36.80
P	15.67	7.04	16.20
K	16.33	83.00	67.80
Ca	12.33	6.00	20.40
Mg	3.87	3.10	2.85
S	6.67		
Micronutrients ($mg.kg^{-1}$)			
B	42.00		
Cu	8.40	3.52	2.93
Fe	323.00	240	0.23
Mn	183.33	755	230.00
Zn	131.00	30.8	53.00

W. microscopic by Appenroth *et al*. (2017) and *Wolffia* sp. by Appenroth *et al*. (2018).

The amount composition of minerals in macrophytes can be manipulated in different production systems (Appenroth et al., 2017; 2018). For example, the levels of micronutrients Cu, Fe, and Zn in the dry biomass of *L. minor* were found to be higher than the levels reported for *W. microscópica* and *Wolffia sp*. produced in a nutrient-enriched solution (Appenroth et al., 2017; 2018). However, the Mn content in *L. minor* was lower than that reported by the same author. Moreover, the levels of macronutrients P and Ca in the dry biomass of *L. minor* were higher than those reported for *W. microscopica* (Appenroth et al., 2017). In contrast, the K content was lower than reported by the same author. The Mg content was similar for both *L. minor* and *W. microscopica*. Compared to *Wolffia sp*., *L. minor* had lower K and Ca content, while its P and Mg content was similar to the levels described by Appenroth et al. (2018).

K/Na, Mg/Ca, and zinc content ratios are essential minerals present in duckweed and used for human consumption (Appenroth et al., 2017). The K/Na limits should be 0.67-37, Mg/Ca 0.05-20, and the Zn content varies from 40 to 1400 $mg.kg^{-1}$ of dry weight (Landolt & Kandeler, 1987). The iron content in the Recommended Dietary Intake (RDA) for adults should remain between 8-18 $mg.kg^{-1}$ (García-Casal et al., 2013).

Additionally, compared to the soybean culture, *L. minor* showed higher mineral content values, highlighting the value 3.6 times for phosphorus, 4.1 times for calcium, 4.6 times for iron, 6 times for manganese, and 3.2 times for zinc (Sfredo, 2008). In this way, our results have shown that duckweed can be used to make high-quality protein isolates similar in nutritional value to soy protein. However, in the case of direct use of duckweed flour for food, it is necessary to observe maximum daily doses to avoid excessive intake of these minerals.

3.3.4. Photosynthetic pigments

The amount of chlorophyll a in the dry biomass of *L. minor* was 4.76 times (Table 14) and 2 times higher than *L. minor* collected from lakes with domestic effluents verified by Radić et al. (2011) and Leblebici & Aksoy (2010), respectively. Furthermore, the amount of chlorophyll b produced in *L. minor* was 4.41 times and 2 times higher than *in L. minor*, verified by the same authors (Table 14).

Table 14. Mean concentrations of photosynthetic pigments (Chl a, Chl b, As, and TC $mg.g^{-1}$).

Pigments	***L. minor****	***L. minor**[a]*	***L. minor**[b]*
Chlorophyll a	3.24	0.68	1.62
Chlorophyll b	1.5	0.34	0.85
Astaxanthin	0,312		
Total carotenoids	0.39	0.28	1.00

L. minor[a] by Radic' *et al*. (2011); *L. minor*[b] by Leblebici & Aksoy (2010), and *L. minor*[c] by Dewanji (1993).

Additionality, the amount of total carotenoids in *L. minor* is higher than those analyzed by Radic' et al. (2011) and lower than those verified by Leblebici & Aksoy (2010). β-carotene found in *L. minor* has an approximate value verified by Dewanji (1993), who used the species from ponds with domestic effluent. The amount of astaxanthin in the aquatic plant was 1.77 times lower than that Wang & Peng (2008) analyzed in the seaweed *C. zofingiensis* produced in a nutrient solution with glucose.

In this way, this study showed that *L. minor* is a species of duckweed with the highest amount of carotenoids, and this plant can explore the potential benefits of consuming these pigments. Carotenoids are essential nutrients that play an important role in humans and animals (Appenroth et al., 2018; Fracalossi & Cyrino, 2013; Eggersdorfer & Wyss, 2018; Elseady & Zahran, 2013; Xu et al., 2022; Hu et al., 2018; Skillicorn et al., 1993). β-carotene is an important photosynthetic pigment, as it acts as a precursor of vitamin A synthesis used as a food supplement (Fracalossi & Cyrino, 2013; Eggersdorfer & Wyss, 2018; Garcia-Casal, 2013). Thus, duckweed species have carotenoid concentrations 10 times higher than terrestrial plants (Skillicorn, 1993). In addition, this plant has antioxidant and anti-inflammatory properties, being used as nutraceutical food (Appenroth et al., 2017; Skillicorn, 1993).

L. minor has a source of astaxanthins, mainly responsible for pigmentation in marine organisms (Hu et al., 2018). Additionally, the efficiency of astaxanthin in *Lemna sp*. for the nutrition of laying hens, improving egg yolk coloring for commercialization, was demonstrated by some research (Akter et al., 2011; Zakaria & Shammout, 2018). Astaxanthin is also a critical stimulant for immunization in humans and animals (Kumar & Bharadvaja, 2020). In addition, it has applications as a food supplement, antioxidant, anti-inflammatory, anticancer, and nutraceutical agent (Hu et al., 2018).

4. CONCLUSION

The *L. minor* promoted the average reduction of supereutrophic trophic to oligotrophic in the effluent. It helped in the improvement of the effluent generated by the IMTA system. The values of crude protein, minerals, fatty acids, and carotenoids in the dry biomass are attractive for use as a bioproduct for functional foods and nutraceuticals. In addition, they can be used as raw material for the food industry or sold to the feed industries, mainly aquaculture. Thus, the results showed the potential use of *L. minor* in an IMTA system for treating effluents and generating new bioproducts from circular production processes practiced in aquaculture family units installed in the Atlantic Forest region.

Industrial relevance

The industrial production of animal protein is expanding worldwide, with aquaculture leading the way. In the Brazilian context, this growth from 2015 to 2022 reached 40.5%, primarily driven by the production of freshwater fish, which accounts for over 75% of the market share. The industrial fish production cycle spans 6 months, with the average input investment representing 85% of the production cost. Within this context, two crucial industrial aspects are intertwined: (1) the impact and the need for water quality remediation, which directly affects the final product, and (2) the necessity of acquiring new value-added co-products that can ensure economic viability. In this regard, using water lentils has proven to be an efficient solution for water bioremediation while also serving as a protein source with an appealing amino acid profile. In this way, the results demonstrated using the 4R strategies: reduce, reuse, recycle, and recover. Besides, it can be described as a circular food economy because it eliminates pollution and waste and regenerates natural systems. Therefore, we can

achieve significant sustainability and resource optimization advancements by implementing circular economy concepts in innovative food production systems.

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CAPÍTULO III

INDICADORES BIOECONÔMICOS DO SISTEMA DE AQUICULTURA INTEGRADA MULTITRÓFICA EM UMA COMUNIDADE TRADICIONAL NO BIOMA DA MATA ATLÂNTICA

RESUMO

Os sistemas de produção aquícola devem incorporar, cada vez mais, os princípios da economia circular, especialmente ao recorrerem a sistemas biológicos e a recursos naturais. Este estudo teve como objetivo avaliar o desempenho bioeconômico de unidades de produção familiar (UPFs) que adotam sistemas de aquicultura convencional e integrada multitrófica (AIMT) no bioma da Mata Atlântica, na região do Vale do Ribeira, São Paulo, Brasil. Ao longo de doze meses, foram acompanhadas três UPFs localizadas em comunidades tradicionais quilombolas que realizam a criação de *Clarias gariepinus* associada ao cultivo de *Lemna minor* em tanques circulares de polietileno de alta densidade com capacidade de 20 m³. Os processos produtivos de baixa escala foram sistematizados e organizados em um modelo de tecnologia social, o que subsidiou a elaboração de um protocolo para a difusão dessa inovação em comunidades rurais. Os subprodutos animais e vegetais gerados nesses sistemas foram analisados quanto ao seu potencial de comercialização. Foram avaliados os custos de implementação e de operação, os dados de produção, os resultados financeiros e a comercialização dos produtos, o que permitiu a aplicação de indicadores de eficiência bioeconômica. Os resultados demonstraram que a organização produtiva fortaleceu a inovação social local, ampliou a replicabilidade do sistema e evidenciou viabilidade econômica e ambiental. O modelo integrado contribuiu para a agregação de valor, para o uso eficiente dos recursos naturais e para o fortalecimento da competitividade das pequenas propriedades rurais.

Palavras-Chaves: aquicultura, aquicultura familiar, bioeconomia, economia circular, tecnologias sociais.

1. INTRODUÇÃO

A crescente preocupação global com as mudanças climáticas, a degradação ambiental e a necessidade de garantir a segurança alimentar têm impulsionado uma profunda reavaliação dos sistemas produtivos e dos modelos de desenvolvimento econômico (Valenti et al., 2021). Nesse contexto, a bioeconomia surge como um paradigma transformador, fundamentado no uso sustentável de recursos biológicos renováveis para gerar alimentos, energia e biomateriais de alto valor agregado. Mais do que um modelo tecnológico, a bioeconomia representa uma estratégia sistêmica de transição para práticas produtivas mais eficientes, inclusivas e de baixo impacto ambiental, integrando ciência, inovação e conservação (KARDUNG et al., 2020). Essa abordagem é particularmente relevante para o setor aquícola, que apresenta elevado potencial para conciliar crescimento econômico, sustentabilidade ecológica e inclusão social, especialmente em comunidades tradicionais dependentes dos recursos aquáticos.

A aquicultura consolidou-se nas últimas décadas como um dos setores agroalimentares de maior crescimento do mundo, responsável por mais de metade do pescado consumido globalmente (FAO, 2020). A piscicultura, em especial, desempenha papel central nesse cenário, mas enfrenta desafios significativos relacionados à qualidade da água, à eficiência produtiva, à variabilidade climática e aos impactos socioambientais associados à intensificação (PAWAR et al., 2020). Tais limitações reforçam a necessidade de desenvolver sistemas produtivos integrados e circulares, que promovam o uso eficiente dos recursos e reduzam as externalidades negativas. Entre as abordagens mais promissoras, destaca-se o Sistema de Aquicultura Integrada Multitrófica (AIMT), no qual espécies de diferentes níveis tróficos são cultivadas de forma complementar, permitindo que os resíduos de uma espécie sirvam de insumos para outra (CHOPIN et al., 2001; TROELL et al., 2009). Essa configuração promove a reciclagem de nutrientes, a mitigação dos impactos ambientais e ganhos de eficiência bioenergética, contribuindo para a sustentabilidade ecológica e econômica dos empreendimentos (HEITZMAN et al., 2024).

Embora a maioria dos estudos sobre o AIMT tenha se concentrado em seus benefícios ambientais e produtivos, o reconhecimento de que sua consolidação depende da aplicação de ferramentas de análise econômica robustas e integradas vem crescendo. A avaliação de indicadores financeiros, energéticos e ecológicos

permite compreender a viabilidade e a resiliência dos sistemas multitróficos sob diferentes condições de manejo (KARDUNG et al., 2020). Além de quantificar custos e retornos, a análise econômica permite mensurar benefícios indiretos, como a valorização de subprodutos, a redução de efluentes e a diversificação de fontes de renda (DOS SANTOS-FILHO et al., 2016). A integração dessas métricas bioeconômicas representa um avanço metodológico essencial para o fortalecimento da bioeconomia azul, ao subsidiar decisões estratégicas, políticas públicas e instrumentos de incentivo baseados na sustentabilidade — como créditos de carbono, pagamento por serviços ecossistêmicos e certificações ambientais.

Dessa forma, o presente estudo teve como objetivo aplicar indicadores bioeconômicos para avaliar o desempenho do Sistema de Aquicultura Integrada Multitrófica (AIMT) em uma comunidade tradicional inserida no bioma Mata Atlântica, no Brasil. Essa análise busca evidenciar como a integração de espécies e fluxos de matéria pode gerar benefícios simultâneos de natureza econômica, social e ambiental, fortalecendo a transição para modelos de produção baseados na bioeconomia azul. Além de contribuir para o conhecimento científico sobre a viabilidade do AIMT em ambientes tropicais, o estudo propõe um referencial metodológico capaz de orientar empreendedores, formuladores de políticas e gestores públicos na implementação de sistemas produtivos resilientes e inclusivos. Assim, ao combinar princípios ecológicos e econômicos, a abordagem bioeconômica aqui apresentada reforça o papel da aquicultura como instrumento estratégico de desenvolvimento sustentável, da segurança alimentar e de valorização dos saberes locais.

2. OBJETIVO

Avaliar a viabilidade econômica de sistemas AIMT conduzidos por unidades de produção familiares no Vale do Ribeira (SP), analisando a integração entre *Clarias gariepinus* e *Lemna minor,* o aproveitamento dos resíduos aquícolas, a produção de coprodutos e os indicadores bioeconômicos, a fim de demonstrar a tecnologia social replicável na aquicultura familiar e nas comunidades tradicionais, baseada na abordagem da economia circular.

3. MATERIAL E MÉTODOS

3.1. Unidades Familiares de Produção (UFPs)

Foram selecionadas 25 propriedades familiares vinculadas à Associação dos Agricultores Familiares do Município de Cajati (AAGFAM), no município de Cajati, São Paulo. Destas, foram selecionadas três UFPs para serem avaliadas neste estudo em conjunto com a AAGFAM, o departamento de "Desenvolvimento Municipal Econômico" e o de "Agricultura e Meio Ambiente" da Prefeitura Municipal de Cajati. Os critérios consideraram: i) serem produtores familiares com disponibilidade de área útil e de recursos naturais para a instalação do sistema de cultivo; ii) serem propriedades que não necessitavam de supressão da vegetação nativa para a instalação dos sistemas produtivos; iii) disponibilidade das UPFs para o manejo e a comercialização dos produtos gerados (Figura 1).

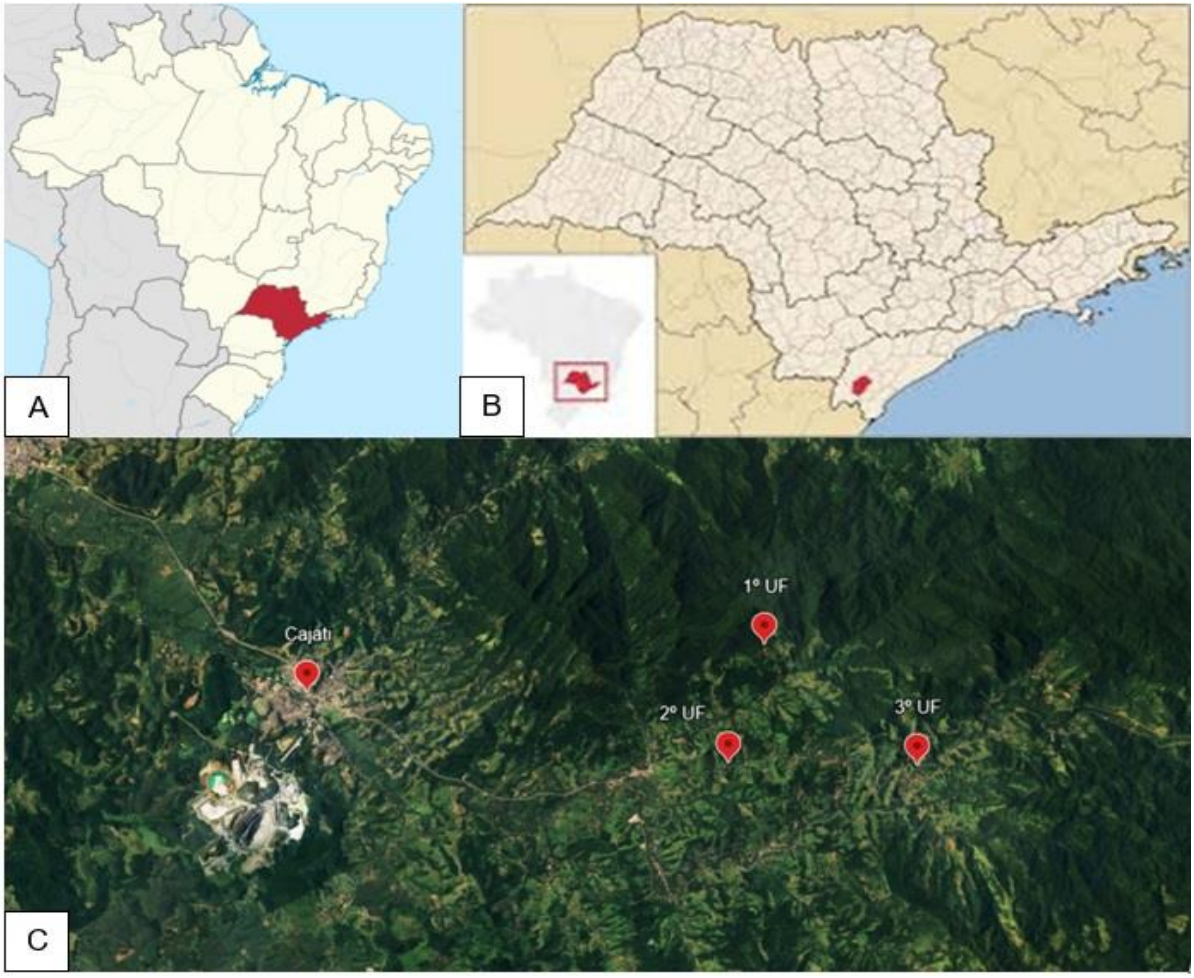


Figura 1. Mapa de localização de acordo com as coordenadas geográficas. A) Estado de São Paulo; B) Município de Cajati, SP na região do Vale do Ribeira; C) Localização das três UFPs na área rural do município.

3.2. Delineamento experimental

O delineamento experimental seguiu os princípios de integração trófica e aproveitamento ecossistêmico entre as espécies *Clarias gariepinus* e *Lemna minor*, conforme descrito por Heitzman et al. (2024), no contexto da Aquicultura Integrada Multitrófica (AIMT) aplicada à aquicultura familiar. Assim, o experimento foi conduzido na zona rural do município de Cajati, São Paulo, abrangendo UFPs da AAGFAM (Tabela 1; Figura 1).

Tabela 1. Localização das três UFPs de aquicultura familiar no município de Cajati, região de Mata Atlântica, Vale do Ribeira, São Paulo, Brasil.

UF	Distância do município (km)	Coordenadas Geográficas	
1	12,5	24º49'47.42''S	48º09'52.66''O
2	11,6	24º48'21.98''S	48º11'13.80''O
3	16,5	24º50'38.79''S	48º12'55.37''O

Em cada UFP, foram avaliados os sistemas de produção convencional (SI), constituídos por um tanque elevado com volume útil de 20 m³ por UFP, destinados exclusivamente à produção direta (PD) de *Clarias gariepinus,* e o sistema de aquicultura integrada multitrófica (SII) (Figura 2). O SII foi implantado de forma complementar ao sistema convencional, combinando o cultivo de *C. gariepinus* com o cultivo de *Lemna minor* que foram cultivados em dois tanques de decantação sequenciais, cada um com capacidade de 500 litros e 1 m² de espelho d'água útil (Figura 3).

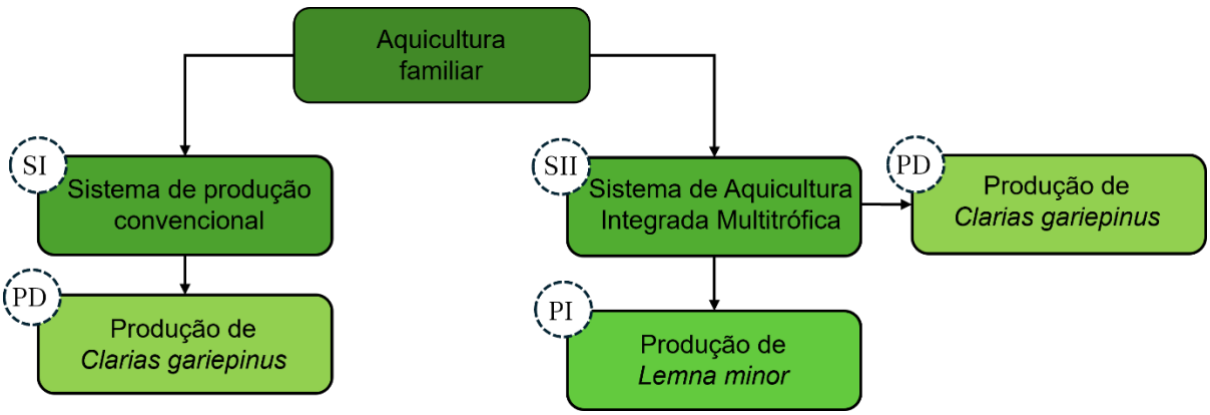


Figura 2. Fluxograma de aquicultura familiar. SI) Sistema de produção convencional de peixe; SII) Sistema de Aquicultura Integrada Multitrófica (AIMT); PD) Produção direta de *C. gariepinus*; PI) Produção indireta de *L. minor*.

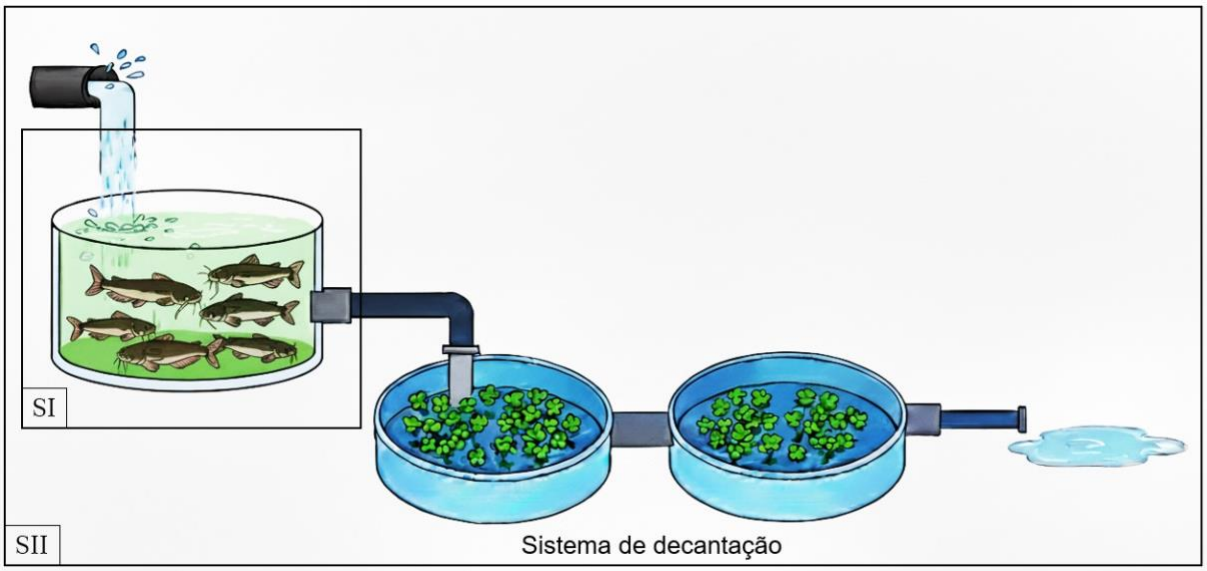


Figura 3. Produção de *Clarias gariepinus* e *Lemna minor* na aquicultura familiar. SI) Sistema convencional de produção de peixe; SII) Sistema de Aquicultura Integrada Multitrófica.

3.3. Produção convencional de Clarias gariepinus

O ciclo produtivo por UFP teve duração de 12 meses. O sistema foi composto por um tanque circular elevado confeccionado em polietileno de alta densidade (PEAD), com volume útil de 20 m³**,** diâmetro de 5,91 m e altura de 1,20 m por UFP (Figura 4). O sistema foi operado em fluxo contínuo de água, sem recirculação. A água foi captada de nascentes ou de corpos d'água adjacentes às propriedades, com vazão média de 0,27 m³/h. Adicionalmente, foi realizada renovação diária de aproximadamente 5% do volume total de água, visando à remoção de sólidos sedimentados.

Foram estocados 2.200 alevinos de *Clarias gariepinus* por tanque de produção, correspondendo a uma biomassa inicial total de 13,20 kg, com peso médio individual de 6 g.peixe^{-1} e comprimento médio entre 8 e 10 cm. Na fase inicial de engorda, estocagem (T_0) a dois meses (T_2), os peixes foram alimentados com ração comercial extrusada para onívoro contendo 42% de proteína bruta (PB) com ração de preço médio de 3,95 reais por quilo cada. A frequência alimentar foi de quatro vezes ao dia, em regime *ad libitum*, nesta fase os peixes apresentaram peso médio de 150 g.peixe^{-1}. A partir do 2º mês (T_2) até o término do ciclo (T_{12}), foi fornecida ração extrusada para onívoro com 35% de PB e a frequência alimentar durante três vezes ao dia, em regime *ad libitum*, com custo médio de 3,90 reais por quilo.

As biometrias foram realizadas, coletando 50 indivíduos por sistema de produção, no início, no meio e no final do ciclo de produção (Figura 5), para medição do comprimento total corporal utilizando um ictiômetro adaptado com calha de PVC e fita métrica seguindo o recomendado por Silva et al (2022) (Figura 5b). No dia anterior à despesca (24 horas), a alimentação dos peixes foi interrompida para promover o esvaziamento do trato gastrointestinal e reduzir o estresse. A despesa com peixes no sistema produtivo contou com uma equipe colaborativa composta por dez produtores rurais associados à AAGFAM em cada UFP participante do projeto de aquicultura (Figura 6).

O produtor responsável pelo tanque de cultivo iniciou o esgotamento total da água com antecedência de três horas em relação à chegada da equipe colaboradora à propriedade (Figura 6a). Posteriormente, os piscicultores familiares efetuaram a captura dos peixes no interior do tanque, utilizando caixas plásticas perfuradas (Figura 6b). Na sequência, os colaboradores posicionados externamente aos tanques foram responsáveis pela aferição individual do peso dos peixes durante a despesca, classificação dos indivíduos conforme a faixa de peso, registro dos dados de pesagem e separação para fins de comercialização (Figura 6c).

Os peixes com peso final até 850 g foram acondicionados em caixas plásticas com gelo na proporção de 3:1 (Figura 6d), transportados em caminhão refrigerado a 2°C, de acordo com o recomendado por Galvão et al. (2022) e destinados à comercialização em indústrias de processamento de pescado (Figura 7a). Os peixes com peso superior a 1.000 g foram alocados em caixas plásticas apropriadas para o transporte de peixes vivos e encaminhados a estabelecimentos de pesque-pague (Figura 7b), ambas localizadas nas regiões Sul e Sudeste do Brasil. O preço médio de comercialização variou entre R$ 4,50 e R$ 5,50 por kg de peixe vivo.

Os parâmetros zootécnicos da produção de *C. gariepinus* integraram o protocolo tecnológico de produção, sendo as análises realizadas ao final da safra de 12 meses. Foram avaliados os seguintes indicadores: densidade de estocagem (peixe.m^{-3}); peso médio inicial (g.peixe^{-1}); biomassa inicial (kg); ganho de peso diário (g.dia^{-1}); peso médio final (g.peixe^{-1}); ganho de peso total (kg); densidade final (peixe.m^{-3}); biomassa final (kg); sobrevivência (%); conversão alimentar; taxa de eficiência alimentar (%); taxa de crescimento específico (%); valor da ração (R$.kg^{-1}); produtividade (kg.m^{-3}).



Figura 4. Implementação do sistema de produção convencional de *C. gariepinus* em tanque elevado PEAD circular 20m³.

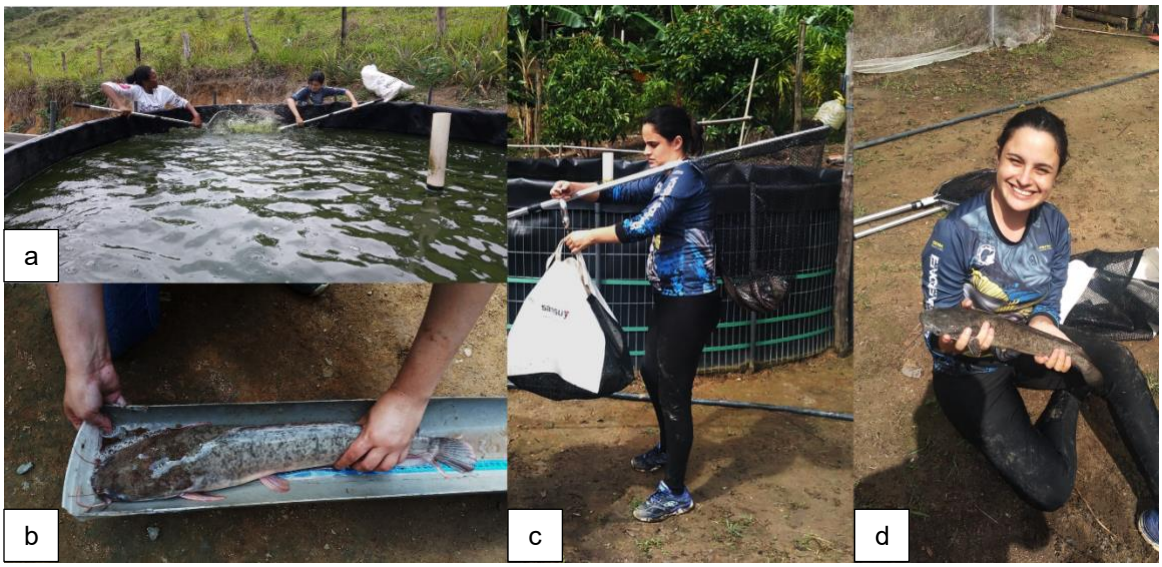


Figura 5. Biometria inicial e final de *C. gariepinus* no sistema convencional de produção, abrangendo as etapas de: a) captura; b) medição do comprimento total; c) determinação do peso corporal médio; d) doutoranda segurando um exemplar de *C. gariepinus* em fase inicial de engorda.



Figura 6. Despesca de *C. gariepinus*. a) Esvaziamento do tanque de cultivo para a coleta dos peixes; b) Captura manual dos peixes vivos; c) Trabalho colaborativo de oito produtores rurais associados à AAGFAM; d) Acondicionamento dos peixes para comercialização.



Figura 7. Comercialização de *C. gariepinus*. a) Indústria de processamento de pescado; b) Transporte de peixe-vivo em caixas de transporte para pesque-pague.

3.4. Produção de Lemna minor em Sistema de Aquicultura Integrada Multitrófica

No sistema convencional de produção, os peixes foram cultivados em tanques circulares elevados confeccionados em Polietileno de Alta Densidade (PEAD), com volume útil de 20m³, diâmetro de 5,91m e altura de 1,20m (Figura 8). O efluente gerado no tanque de produção de peixe foi direcionado para a saída do sistema, conduzido por gravidade, com vazão média de 0,27 m^3/h, passando por dois tanques circulares de decantação com capacidade de 500 litros cada e 1 m² de espelho d'água útil, destinados exclusivamente à retenção de resíduos sólidos, sem recirculação de água.

Os resíduos líquidos, por sua vez, foram direcionados para irrigação da vegetação nativa na floresta Atlântica (Figura 8a). No entanto, o processo de decantação do sistema não apresentava plena eficiência, o que levava à mistura dos resíduos sólidos com a fração líquida do efluente (Figura 8b), exigindo a limpeza mensal dos tanques de decantação.

O Sistema de Aquicultura Integrada Multitrófica (AIMT) foi implementado seguindo a metodologia de Heitzman et al. (2024), com a inserção do cultivo de lentilha d'água *(Lemna minor)* no sistema de decantação subsequente ao tanque de produção de *Clarias gariepinus*, em cada UFPs (Figura 9). Inicialmente, foram pesados 15 g de biomassa fresca de *L. minor* (Figura 10) e adicionadas em cada tanque de decantação contendo resíduos sólidos e líquidos. Entretanto, após 15 dias de cultivo, foi observado que o crescimento da biomassa cessou (Figura 11a). Dessa maneira, foi realizada a limpeza dos tanques de decantação, os quais foram reabastecidos com o efluente proveniente da produção de peixes e, em seguida, adicionadas novamente 15g de biomassa fresca de *L. minor* (Figura 11b). Após a reinserção da biomassa nos tanques limpos, ocorreu o restabelecimento do crescimento e desenvolvimento da macrófita (Figura 11c) nos tanques.

O cultivo de *Lemna minor* nas UFPs foi conduzido ao longo de 12 meses. A coleta da biomassa fresca da macrófita foi realizada mensalmente, utilizando-se de peneiras manuais para a remoção integral da vegetação presente nos tanques de decantação. Após a remoção, foi realizada à reintrodução de 15g de biomassa fresca por tanque (Figura 11b), de modo a padronizar a densidade inicial de cultivo em cada ciclo de monitoramento.

Foram realizadas as análises dos dados de produção da biomassa fresca e seca de *Lemna minor* de acordo com a taxa de crescimento relativa (TCR) (Equação 1) e a produção anual ($t^{-1}.ha^{-1}.ano^{-1}$), calculada a partir da variação da biomassa fresca durante o ciclo de produção.

$$TCR = \frac{\ln \text{peso final} - \ln \text{peso inicial}}{\text{tempo final} - \text{tempo inicial}} x100 \quad (1)$$



Figura 8. Sistema convencional de produção de *C. gariepinus*. a) Tanques de decantação instalados após o sistema de cultivo de peixe; b) Mistura dos resíduos sólidos com a fração líquida do efluente.



Figura 9. Sistema Aquicultura Integrada Multitrófica (AIMT) em tanques elevados utilizados nas unidades familiares de produção (UFPs) da Associação de Agricultores Familiares de Cajati – AAGFAM.



Figura 10. Pesagem de 15g de *Lemna minor*.

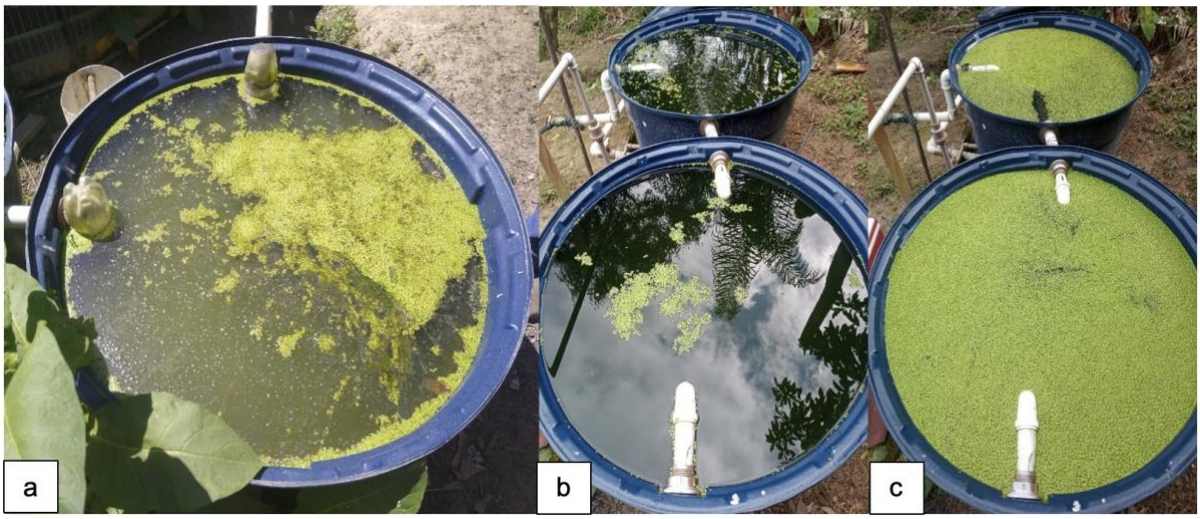


Figura 11. Sistema de decantação do sistema AIMT com *Lemna minor*. a) Inserção da biomassa fresca no sistema contendo resíduos sólidos e fração líquida; b) Reinserção lentilha d'água após a limpeza dos tanques; c) Desenvolvimento da macrófita no sistema de decantação.

3.3. Parâmetros físico-químicos dos efluentes

As análises físico-químicas dos efluentes foram realizadas por Unidade Familiar de Produção (UFP) no sistema de produção convencional (SI) de *Clarias gariepinus* e no sistema de Aquicultura Integrada Multitrófica (SII) com *Lemna minor*, de acordo com a metologia de Heitzman et al. (2024).

No sistema convencional (SI) foram realizadas as análises físico-químicas em dois pontos: água de entrada (Ponto 1), efluente do sistema de produção de peixes (ponto 2). No SII a análise foi realizada no Ponto 1, Ponto 2 e Ponto 3, efluente do sistema de decantação (Figura 12). As coletas em ambos os sistemas foram realizadas simultaneamente, assegurando comparabilidade entre os tratamentos.

Os parâmetros físicos da água foram medidos na UFP experimental. Foi utilizado o Medidor Multiparamétrico - Asko® ASK88, que determinou a temperatura (ºC), pH, oxigênio dissolvido (OD) e condutividade elétrica (CE). Em seguida, amostras de efluentes foram coletadas nos pontos de monitoramento e armazenadas em frascos plásticos de 900mL (Figura 13), acondicionados em caixas isotérmicas a 5 °C para preservação das características físico-químicas e foram transportadas ao laboratório da Universidade Estadual Paulista (UNESP) – Faculdade de Ciências Agrárias do Vale do Ribeira, município de Registro, SP. Os parâmetros químicos da água foram analisados em laboratório utilizando o Medidor Multiparamétrico Impermeável - Asko® Micro 20, que determinou os níveis de amônia (NH_3), nitrito (NO_2), nitrato (NO_3^-) e fosfato (PO_4^{3-}).

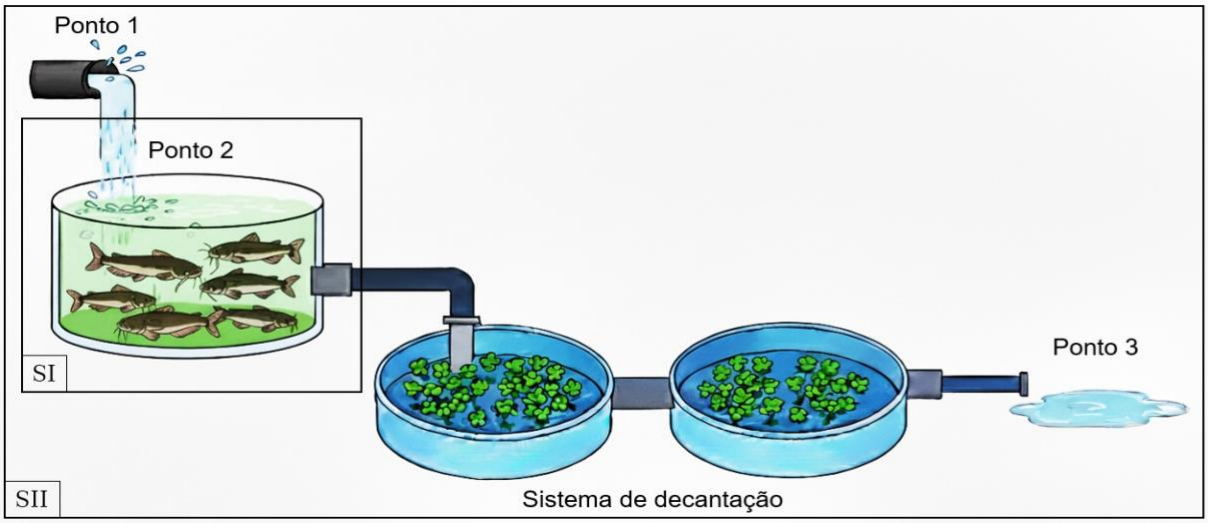


Figura 12. Produção de *Clarias gariepinus* e *Lemna minor* na aquicultura familiar. SI) Sistema convencional de produção de peixe; SII) Sistema de Aquicultura Integrada Multitrófica. Ponto 1) Água de captação; Ponto 2) Efluente do sistema de produção de peixes; Ponto 3) Efluente do sistema de decantação. *Adaptado Heitzman et al. (2024).*

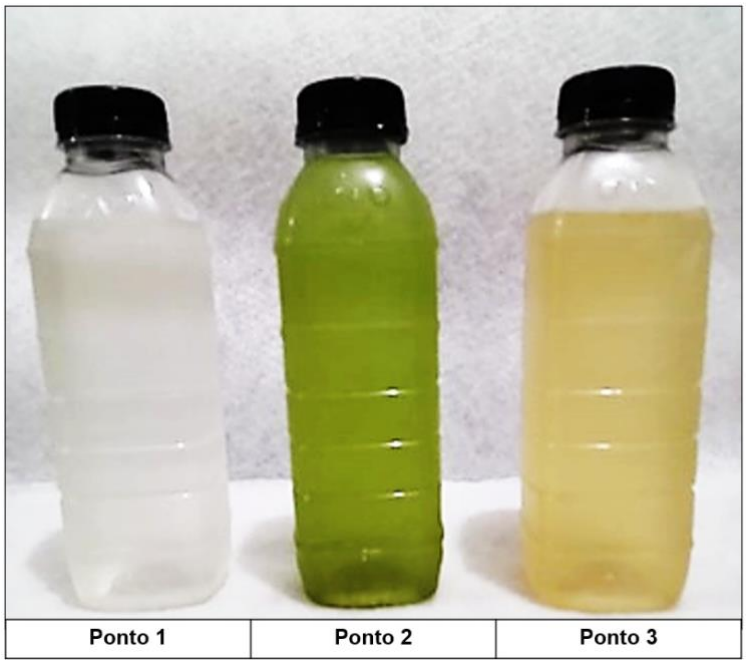


Figura 13. Coleta de efluentes dos sistemas I e II. Ponto 1) Água de captação; Ponto 2) Efluente do sistema de produção de peixes; Ponto 3) Efluente do sistema de decantação.

3.3. Processamento de biomassa fresca de L. minor

A biomassa fresca de *Lemna minor* foi coletada nas UFPs (Figura 14a) e o excesso de água foi removido manualmente. Em seguida, a biomassa foi embalada em sacos plásticos, seguindo o recomendado por Silva et al. (2022) (Figura 14b) devidamente identificados e transportada ao Laboratório de Tecnologia da Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias do Vale do Ribeira, Registro, SP, para posterior processamento e análise. A biomassa de *Lemna minor* foi submetida ao processamento mínimo viável para a obtenção da farinha, seguindo um protocolo padronizado de preparo, conforme descrito em Heitzman et al. (2024).

Inicialmente, a biomassa fresca foi lavada em água corrente (Figura 14c), utilizando-se peneiras domésticas até que o efluente apresentasse aspecto límpido e transparente. Em seguida, 1 kg de biomassa fresca foi distribuído uniformemente em bandejas de aço inoxidável (47 × 59 cm) (Figura 14d) e submetido à secagem por 24 horas a 45 °C, em estufa com circulação e renovação de ar (Teknal®) (Figura 15a), até atingir umidade residual adequada para moagem. Após a secagem (Figura 15b), o material foi triturado (Figura 15c) em processador de grãos doméstico (Philips Wallita®) até obtenção de uma farinha homogênea de *L. minor* (Figura 16).

A farinha vegetal obtida foi embalada a vácuo em sacos plásticos herméticos transparentes, utilizando equipamento industrial de selagem a vácuo (R. Baião®) (Figura 15d), e armazenada em temperatura ambiente. Foi calculada o rendimento da biomassa seca (%):

$$\text{Rendimento (\%)} = \frac{Peso\ seco\ (g)}{Peso\ fresco\ (g)}\ x100 \text{ (X)}$$

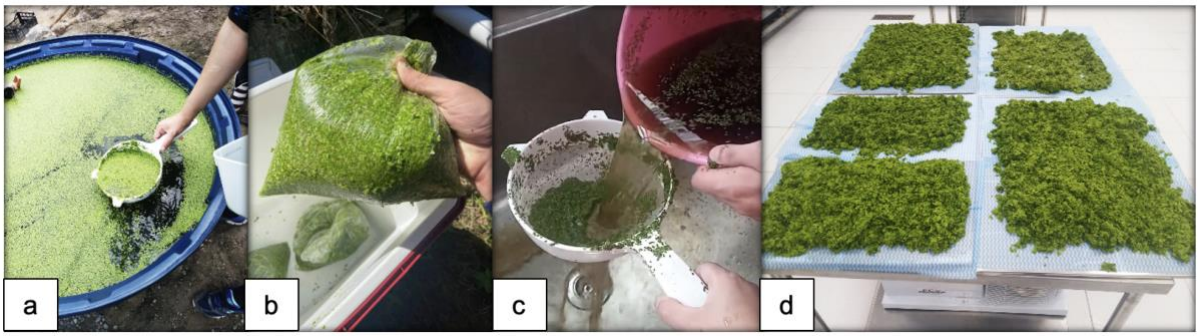


Figura 14. Processamento de biomassa fresca de *Lemna minor*. a) Coleta; b) Embalagem para transporte; c) Lavagem da biomassa; d) Biomassa separadas em bandejas de 1kg para secagem.



Figura 15. Processamento da biomassa seca de *Lemna minor*. a) Secagem; b) biomassa seca; c) Trituração; d) Embalagem à vácuo.

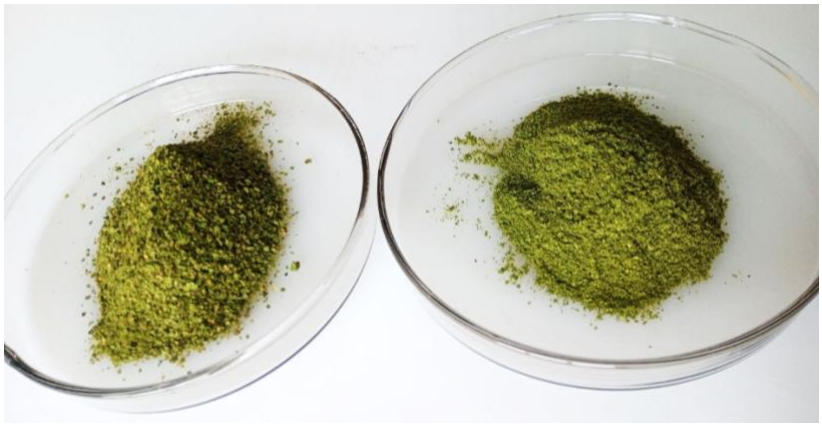


Figura 16. Farinha vegetal de *Lemna minor*.

3.4. Serviços ecossistêmicos e produtos do sistema AIMT

Foi elaborado um portfólio que incluiu os bioprodutos com potencial de comercialização e os serviços ecossistêmicos gerados no Sistema AIMT implementado a partir da produção comercial de *Clarias gariepinus*, biomassa fresca de *Lemna minor* e matéria-prima em pó (biomassa seca). As informações obtidas foram incorporadas à tabela de receitas complementares do sistema produtivo, cujos valores econômicos foram estimados e expressos em $R\$.kg^{-1}.safra^{-1}$. Todos os resultados foram organizados e sistematizados em planilhas eletrônicas seguindo o recomendado por Engle et al (2010), com o propósito de subsidiar a aplicação do modelo de análise bioeconômica proposto para o sistema de produção em estudo.

3.5. Indicadores bioeconômicos do sistema AIMT

Foram analisados os dados bioeconômicos e os custos operacionais relacionados aos insumos empregados na produção de *Clarias gariepinus*, incluindo: custo da ração, preço de aquisição dos alevinos, despesas com mão de obra direta, encargos administrativos, investimentos em capacitação técnica e treinamentos dos aquicultores familiares, consumo de energia elétrica, entre outros desembolsos operacionais. Adicionalmente, foi realizada uma análise comparativa entre os indicadores econômicos da produção convencional de *C. gariepinus* e aqueles obtidos a partir do sistema de Aquicultura Integrada Multirófica (AIMT), utilizando *Lemna minor*.

Aplicamos a metodologia de Engle (2010) para avaliar os indicadores financeiros e modelagem bioeconômica. A receita foi calculada como variável dependente de uma função, estimada com base em variáveis independentes, tais como o preço de comercialização dos animais (Pc) e a biomassa produzida (produção). De forma análoga, os custos de produção foram estimados com base nas quantidades dos insumos utilizados (Qi) e nos respectivos preços unitários (Wi). Com base nessas estimativas, os lucros foram determinados como a diferença entre a receita total e os custos totais de produção. Todos os valores foram corrigidos monetariamente para o ano-base de 2025, a fim de garantir a comparabilidade temporal e a consistência econômica dos resultados.

As variáveis de custo no modelo bioeconômico consideraram os seguintes desembolsos como custos variáveis (CV): ração (Cr), alevinos (Ca), manejo sanitário

(Cms), treinamento (Ctr), contribuição especial para a seguridade rural (CESSR) e combustível (Cco). Como custos fixos (CF), incluíram-se os desembolsos com: energia elétrica (Cee), mão de obra (Cmo), manutenção (Cma), administrativo (Cad), arrendamento (Car) e depreciação (D).

Os preços (W) dos desembolsos de cada insumo foram estimados com base nos dados das Unidades de Produção Familiar (UFPs) analisadas; utilizou-se o custo unitário por animal produzido para todos os insumos, exceto a ração (Cr), cujo valor foi estimado com base no preço por quilograma (Wr). Os valores de desembolsos com depreciação foram desconsiderados nas análises principais, porém incluídos como valor por unidade produzida apenas para fins de estimativas de dedução contábil por quilograma produzido. Posteriormente, esses valores foram reintroduzidos no fluxo de caixa para a análise de viabilidade econômica. A estimativa de depreciação foi realizada com base no método linear, considerando 8% do investimento mínimo necessário para esta modalidade produtiva, conforme proposto por Engle (2010).

Na sequência, procedeu-se à otimização do gerenciamento financeiro aplicado à produção comercial das UPFs, com base na integração de variáveis financeiras e produtivas, estas últimas associadas à produção de peixes, macrófitas e bioprodutos derivados. Essa etapa baseou-se na formulação da equação de estimativa de lucros ajustados (L'), obtida pela substituição dos termos da receita total (R) e dos custos totais (C) na Equação 3. As expressões matemáticas utilizadas para essa substituição foram definidas conforme as seguintes equações:

$$L = (R - C) \qquad (3)$$

$$L' = \left[\left[\left|[(DE.VP).(1 - MOR)].\langle\{Pi^{(EXP)} + [(0{,}01.TGC).\sum_{i=1}^{n}(TA_i.CP_i)]\}^{\left(\frac{1}{EXP}\right)}\rangle\right|.Pc\right| - C''\right]$$

Receita Estimada

Nº de peixes finais — *Peso final dos peixes (kg)*

Biomassa ou Produção (kg)

Calculou-se o imposto de renda (IR) (Equação 4) a partir da seguinte equação matemática:

$$IR = (L'.\ \%IR) \quad (4)$$

$$IR' = \overbrace{\left[\left[\left[(DE.VP).(1-MOR)\right].\left\langle\left\{Pi^{(EXP)} + \left[(0{,}01.TGC).\sum_{i=1}^{n}(TA_i.CP_i)\right]\right\}^{\left(\frac{1}{EXP}\right)}\right\rangle\right|.Pc\right| - C''\right]\right]}^{\text{Receita Estimada}}.\%IR$$

$$\text{Lucro Bruto (Antes do IR)}$$

Em seguida, estima-se o lucro líquido (LL') (Equação 5), lucro livre de imposto de renda (IR), conforme a seguinte equação:

$$LL' = (L' - IR') \quad (5)$$

Por meio dos indicadores de custos e lucratividade, foi comparada a aplicação da modelagem bioeconômica. Dentre os indicadores financeiros, utilizamos o indicador de receita estimada (RE) (Equação 6), custo variável (CV) (Equação 7), custo fixo (CF) (Equação 8), custo total (CT) (Equação 9), lucro bruto (LB) (Equação 10), lucro líquido (LL) (Equação 11), margem bruta (MB) (Equação 12) e margem líquida (ML) (Equação 13), ambos os indicadores por unidade produzida (em quilograma), mediante as seguintes equações:

$$RE\ (R\$.kg^{-1}) = \left(\frac{R'}{P'}\right) \quad (6) \qquad CV\ (R\$.kg^{-1}) = \left(\frac{CV}{P'}\right) \quad (7) \qquad CF\ (R\$.kg^{-1}) = \left(\frac{CF}{P'}\right) \quad (8)$$

$$CT\ (R\$.kg^{-1}) = \left(\frac{CT}{P'}\right) \quad (9) \qquad LB\ (R\$.kg^{-1}) = \left(\frac{L'}{P'}\right) \quad (10) \qquad LL\ (R\$.kg^{-1}) = \left(\frac{LL'}{P'}\right) \quad (11)$$

$$MB\ (\%) = \left[\left(\frac{LB}{RE}\right).100\right] \quad (12) \qquad ML\ (\%) = \left[\left(\frac{LL}{RE}\right).100\right] \quad (13)$$

Sendo, P' = biomassa produzida no sistema AIMT (kg.safra^{-1}).

Posteriormente, foram estimados os indicadores de custos e lucratividade, os valores de receita, incluindo os potenciais bioprodutos deste sistema AIMT. Os custos e lucros foram adicionados a um fluxo de caixa (FC) para a sequência de cálculos dos indicadores de viabilidade bioeconômica.

Foram utilizados os quatro principais indicadores para verificar a viabilidade econômica de no sistema convencional de peixe e no sistema AIMT. Assim, foi avaliado a taxa interna de retorno (TIR) (Equação 14), valor presente líquido (VPL) (Equação 15), período de retorno do capital (*Payback*) (Equação 16) e relação custo-benefício do investimento (RCB) (Equação 17). Estes indicadores foram calculados

de acordo com a metodologia proposta por Engle (2010), conforme as seguintes equações:

$$\sum_{t=1}^{n}\left[\frac{FLC_t}{(1+TIR)^t - FLC_0}\right]^{TMA} = 0 \quad (14) \qquad VPL = \sum_{t=1}^{n}\left[\frac{FLC_t}{(1+TMA)^t - FLC_0}\right] \quad (15)$$

Payback é o tempo *t* descontado de uma determinada taxa de juros, que neste estudo utilizamos a TMA estimada em juros reais, quando:

$$\sum_{t=0}^{n}(FLC)^{TMA} = 0 \quad (16) \qquad RCB = \sum_{t=1}^{n}\left[\frac{FLC_t}{\frac{(1+TMA)^t}{FLC_0}}\right] \quad (17)$$

Sendo, FLC = fluxo líquido de caixa, TMA = taxa mínima atrativa, n = horizonte do projeto em anos (0, 1, 2, 3... n) e t = tempo em anos.

A taxa mínima atrativa (TMA) (Equação 18) foi estimada a uma taxa de juros reais, a qual será considerada como taxa de juros nominal a meta da taxa básica de juros (Serviço Especial de Liquidação e Custódia, Selic em outubro de 2025) somada à taxa média de juros dos certificados de recebíveis do agronegócio (CRA). Em função da meta de taxa de inflação para o período de realização deste projeto (corrigida para outubro de 2025), o CRA é o fator de prêmio ou risco assumido na estimativa da TMA em juros reais. Para isto, utilizamos a metodologia proposta por Erlich & Moraes (2015), apresentada na equação:

$$TMA_{juros\ reais} = \left|\left[\frac{(1 + (\overbrace{Selic_{2019}}^{\text{Taxa Nominal de Juros}} + \overbrace{CRA_{2019}}^{\text{Prêmio ou Risco}}))}{(1 + inflação_{2019})}\right] - 1\right| .100 \quad (18)$$

4. RESULTADOS E DISCUSSÃO

4.1. Parâmetros físico-químicos na produção de Clarias gariepinus

O *Clarias gariepinus* apresenta ampla tolerância às variações dos parâmetros físico-químicos da água (HECHT; BRITZ, 1988), característica que contribui para sua adaptabilidade a diferentes sistemas de cultivo (IMAM, 2019; OKOMODA, 2019; DAFF, 2018; FAO, 2025). No entanto, o desempenho zootécnico depende da manutenção desses parâmetros em faixas adequadas, especialmente em sistemas de produção de maior intensidade (HECHT; BRITZ, 1988; DAFF, 2018; FAO, 2025).

A temperatura da água variou entre 29,20°C no quarto mês de cultivo (T_4) e 16,40°C no oitavo mês (T_8), com média final próxima de 24°C (T_{12}) (Figura 17). Esses valores encontram-se dentro da faixa de tolerância térmica para o crescimento de *C. gariepinus*, entre 8°C e 35°C (HECHT; BRITZ, 1988; LANGI, 2024; FAO, 2025). Entretanto, temperaturas entre 28°C e 30°C (T_4), período do verão, tendem a acelerar o metabolismo da espécie, demandando maior consumo de ração e intensificando o metabolismo energético (HECHT; BRITZ, 1988; LANGI, 2024; FAO, 2025). No período intermediário (T_8), foi observado o ponto mínimo de temperatura, início do inverno, coincidindo com a redução na taxa de crescimento e ganho de peso, evidenciando a influência térmica direta sobre o metabolismo e a eficiência alimentar da espécie (HECHT; BRITZ, 1988; FAO, 2025).

O potencial hidrogeniônico (pH) reduziu de 9,00 ± 0,20 (T_0) para 6,56 ± 0,43 (T_4) nas UFPs e se manteve relativamente estável ao longo do ciclo de produção (T_8 = 6,52 ± 0,45; T_{12} = 6,19 ± 0,36) (Figura 17). A diminuição observada entre T_0 e T_4 podem estar relacionadas à origem da água utilizada no abastecimento dos tanques, proveniente de nascentes ou corpos d'água naturais adjacentes às propriedades, com características ligeiramente alcalinas no momento da captação.

O pH médio manteve-se dentro da faixa recomendada para o cultivo de *Clarias gariepinus* (Figura 17), entre 6,5 e 8,0 (NDUBUISI et al., 2015; DAFF, 2018; FAO, 2025). No entanto, na fase final de engorda (T_8 a T_{12}), foi observado um leve decréscimo nos valores, o que, embora ainda dentro da faixa aceitável para a produção de peixes (6,0 a 9,0) (LEIRA et al., 2013), merece atenção, visto que a exposição prolongada a valores inferiores a 6,0 pode comprometer o crescimento e o desenvolvimento da espécie (NDUBUISI et al., 2015).

O oxigênio dissolvido (OD) reduziu de 7,70 ± 1,30 mg.L^{-1} (T_4) a 2,26 ± 2,15 mg.L^{-1} (T_{12}) (Figura 17), valor inferior ao mínimo recomendado de ≥ 5 mg.L^{-1} para a espécie (DAFF, 2018; IMAM et al.,2019; FAO, 2025). Embora concentrações reduzidas de OD não representem fator limitante à sobrevivência da espécie, devido à sua capacidade de respiração aérea facultativa que permite tolerância a níveis quase nulos de oxigênio (HECHT; BRITZ, 1988), valores abaixo de 3,0 mg.L^{-1}, observados entre T_8 a T_{12}, podem comprometer o desempenho produtivo, ocasionando redução do metabolismo e consequentemente, desaceleração do crescimento (IMAM et al., 2019).

Assim, a manutenção de níveis adequados de OD é essencial para otimizar o ganho de peso, a eficiência alimentar e o desempenho metabólico dos peixes, especialmente em sistemas de cultivo com maior densidade de estocagem (HECHT; BRITZ, 1988; HOSSAIN et al., 2001; DAFF, 2018; LANGI, 2024; FAO, 2025).

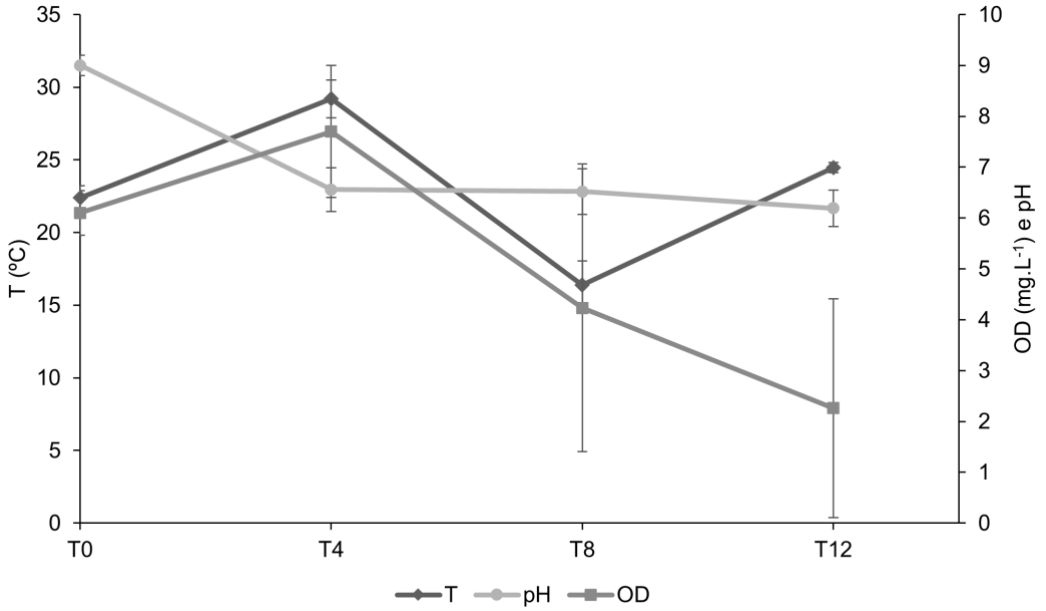


Figura 17. Valor médio dos parâmetros físico-químicos dos efluentes nas três UFPs ao longo do ciclo de produção de *C. gariepinus*. Introdução dos peixes (T0); quatro meses (T4); oito meses (T8); despesca (T12); temperatura (ºC); potencial hidrogeniônico (pH); Oxigênio dissolvido (OD; mg.L^{-1}).

A condutividade elétrica (CE) apresentou variação entre 24,00 µS.cm^{-1} (T_0) e 321,52 µS.cm^{-1} (T_{12}) (Figura 18). Até o oitavo mês de cultivo (T_8), os valores permaneceram abaixo da faixa recomendada para o cultivo de *Clarias gariepinus*, que varia entre 100 e 2.000 µS.cm^{-1} (STONE; THOMFORDE, 2003), indicando acentuada

produção primária no sistema aquático (LEIRA et al., 2013). No período subsequente, entre T_8 e T_{12}, foi observada acentuada elevação da CE, indicando aumento da decomposição da matéria orgânica e do acúmulo de nutrientes dissolvidos (LEIRA et al., 2013). De acordo com Imam et al. (2019), flutuações moderadas na faixa de 200 a 410 µS.cm^{-1} não comprometem o crescimento nem a sobrevivência da espécie.

A concentração de fosfato (PO_4) variou ao longo do período experimental (Figura 18), sendo observados os valores mais elevados no quarto mês (T4) durante o verão (28,00 ± 3,94 mg.L^{-1}) e os menores no oitavo mês (T8), correspondente ao período de inverno (2,43 ± 1,44 mg.L^{-1}). Entretanto, Segundo a Resolução CONAMA nº 357/2005, a concentração de fósforo total em corpos d'água doces, em condições de boa qualidade ecológica, deve ser da ordem de ≤ 0,05 mg.L^{-1} (50 µg.L^{-1}) em ambientes lenticos e ≤ 0,1 mg.L^{-1} em ambientes lóticos, o que é muito inferior aos picos observados no presente estudo. O PO_4 é um dos indicadores da qualidade da água, pois níveis elevados estão diretamente associados à proliferação de algas e ao grau de eutrofização dos sistemas aquáticos (ESTEVES, 1998; LEIRA et al., 2017; DE QUEIROZ et al., 2021; HEITZMAN et al., 2024)

Em sistemas de piscicultura, o excesso de ração não consumida e a excreção dos peixes constituem as principais fontes de fósforo dissolvido (ZHANG; FANG, 2006; MACEDO; TAVARES, 2010; QUEIROZ et al., 2021), o que favorece o enriquecimento trófico e a deterioração da qualidade da água (ZHANG; FANG, 2006; MACEDO; TAVARES, 2010; QUEIROZ et al., 2021). Entretanto, níveis moderados de PO_4 podem exercer efeitos positivos sobre o desempenho zootécnico de *Clarias gariepinus* (STRAUCH et al., 2019).

Segundo Strauch et al. (2019), concentrações entre 40 e 80 mg.L^{-1} de PO_4 não afetam negativamente o crescimento ou o bem-estar dos peixes, resultando em maiores taxas específicas de crescimento e eficiência alimentar. No entanto, concentrações excessivas, como 120 mg.L^{-1} (PO_4), podem comprometer o bem-estar animal, reduzindo a atividade natatória, a respiração aérea e ocasionando alterações na coloração e integridade da pele. Dessa forma, embora o fósforo seja essencial ao metabolismo e à mineralização óssea, seu acúmulo em níveis elevados no sistema representa risco potencial ao desempenho fisiológico dos peixes (STRAUCH et al., 2019) e na qualidade ambiental (STRAUCH et al., 2019; HEITZMAN et al., 2024).

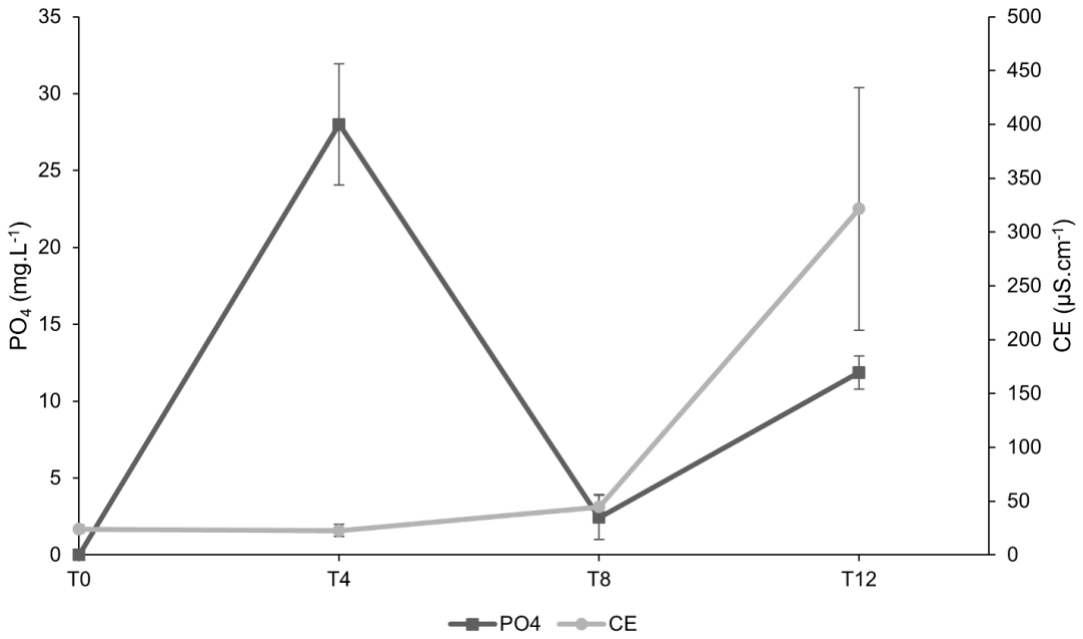


Figura 18. Valor médio dos parâmetros físicos dos efluentes nas três UFPs durante o ciclo de produção de *C. gariepinus*. Introdução dos peixes (T0); quatro meses (T4); oito meses (T8); despesca (T12); Fosfato (PO_4); Condutividade elétrica (CE).

Durante o ciclo de produção (T_0 a T_{12}), foi observada variação nos níveis de compostos nitrogenados no efluente das UFPs (Figura 19). No início do cultivo (T_0) não foram detectadas concentrações de nitrogênio amoniacal total (NH_4^+) e nitrito (NO_2^-), enquanto nitrato (NO_3^-) apresentou valor médio de 2,08±0,08 $mg.L^{-1}$ possivelmente associado à presença residual na água de abastecimento.

No quarto mês (T_4), correspondente ao período de verão e à fase de rápido crescimento dos peixes (peso médio entre 318 e 643 $g.peixe^{-1}$), ocorreu o pico da [NH_4^+] 15,20±0,74 $mg{\cdot}L^{-1}$ e dobrou a [NO_3^-] para 4,07±1,45 $mg.L^{-1}$. No período correspondente ao início do inverno (T_8) houve a redução da [NH_4^+] e o início da elevação de [NO_3^-] (8,43±2,97 $mg.L^{-1}$), e posteriormente foram observadas altas concentrações de nitrito (17,38±12,53 $mg.L^{-1}$) e nitrato (20,43±11,27 $mg.L^{-1}$) no efluente (T_{12}).

O processo de nitrificação corresponde à oxidação biológica de compostos nitrogenados, tanto orgânicos quanto inorgânicos, realizada por microrganismos autótrofos que convertem amônia em nitrito e, posteriormente, em nitrato (STONE; THOMFORDE, 2004; MORO et al., 2013; LEIRA et al., 2017). A maioria dos peixes possuem baixa tolerância as concentrações dos compostos nitrogenados dissolvidos na água (MORO et al., 2013; LEIRA et al., 2017), porém o *Clarias gariepinus* destaca-

se por sua elevada resistência, tolerando concentrações de até 5 $mg.L^{-1}$ de amônia (NH_4^+) (STONE; THOMFORDE, 2004), 2 $mg.L^{-1}$ de nitrito (NO_2^-) (STONE; THOMFORDE, 2004; ROQUES et al., 2015) e 620 $mg.L^{-1}$ de nitrato (NO_3^-) (SCHRAM et al., 2014). Apesar dessa tolerância, valores acima desses limites podem reduzir o metabolismo, inibir o apetite, comprometer o ganho de peso e, em casos extremos, causar mortalidade na espécie (STONE; THOMFORDE, 2004; SCHRAM et al., 2014; ROQUES et al., 2015).

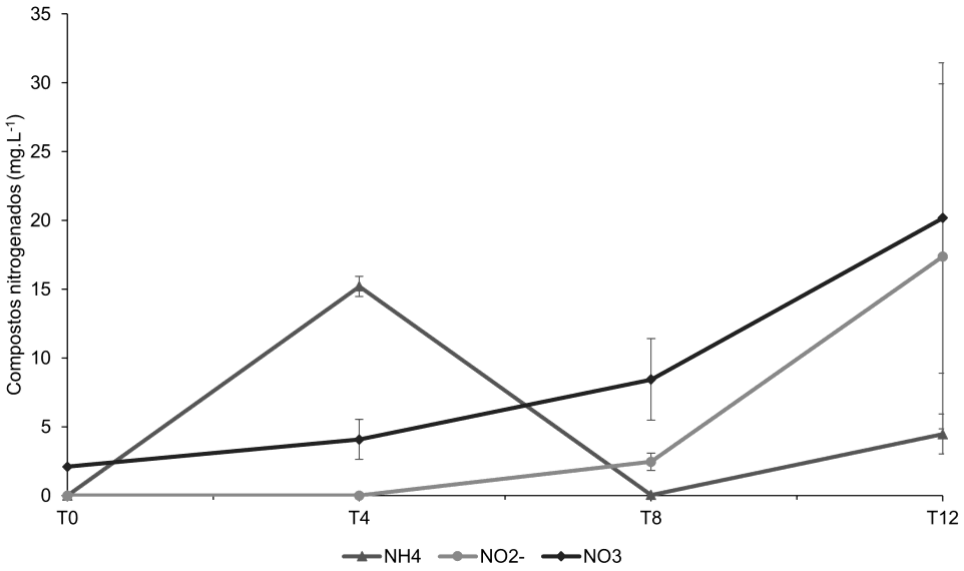


Figura 19. Valor médio dos compostos nitrogenados dos efluentes nas três UFPs durante o ciclo de produção de *C. gariepinus*. Introdução dos peixes (T0); quatro meses (T4); oito meses (T8); despesca (T12); Nitrogênio amoniacal total (NH_4); Nitrito dissolvido (NO_2^-); Nitrato dissolvido (NO_3).

4.2. ***Desempenho zootécnico de Clarias gariepinus***

A densidade de estocagem inicial adotada nas três UFPs observadas no município de Cajati foi de 0,660 $kg.m^{-3}$ equivalente à 110 $peixes.m^{-3}$ (Tabela 2), valor que se enquadrou na categoria de sistema semi-intensivo para *Clarias gariepinus*, cuja densidade inicial varia entre 26 $peixes.m^{-3}$ (HECHT, 2013) e 200 $peixes.m^{-3}$ (FAO, 2025) para tanques elevados de concreto e viveiros escavados.

Ao final do ciclo produtivo (T_{12}), a densidade média observada foi de 69,50 $kg.m^{-3}$ equivalente à 83 $peixes.m^{-3}$ (Tabela 2), resultado superior ao registrado por Hecht (2013) para produção familiar em tanques elevados de concreto (38 $kg.m^{-3}$), porém inferior aos valores típicos de sistemas intensivos em viveiros escavados e tanques elevados de concreto, sem recirculação de água (200–300 $kg.m^{-3}$) (DAFF,

2018) e superintensivos em Sistemas de Recirculação Aquícola (RAS)(>700 kg.m^{-3}) para a espécie (FAO, 2025).

Nas UFPs avaliadas, o tempo total de cultivo foi de doze meses (T_{12}), superior ao reportado por DAFF (2018), que indicou um ciclo médio de oito meses para *Clarias gariepinus* em sistemas comerciais de fluxo contínuo, e também superior ao ciclo descrito pela FAO (2025), de seis meses em aquicultura familiar em sistema com baixa renovação de água, ambos alcançando peso médio individual próximo de 1kg. Nas UFPs, o peso médio final dos peixes foi de 794 g.peixes^{-1} após doze meses de produção, valor inferior ao observado por HECHT (2013), DAFF (2018) e FAO (2025), indicando que o prolongamento do ciclo produtivo não resultou em ganhos proporcionais de biomassa.

Tabela 2. Parâmetros zootécnicos da produção de *C. gariepinus* em três UFPs de aquicultura familiar no município de Cajati, São Paulo.

Parâmetros zootécnicos	UFPs			Média
	1	2	3	
Densidade inicial (kg.m^{-3})	0,660	0,660	0,660	0,660 ± 0,00
Peso médio inicial (g.peixe^{-1})	6,40	6,10	6,35	6,00 ± 0,00
Biomassa inicial (kg)	13,70	13,20	13,30	13,20 ± 0,00
Densidade final (kg.m^{-3})	72,50	68,00	59,00	83,00 ± 3,46
Peso médio final (g.peixe^{-1})	844,00	794,00	744,00	794,00 ± 50,00
Biomassa final (kg)	1.450,00	1.360,00	1.180,00	1.330,00 ± 137,48
Ganho de peso total (kg)	1.223,80	1.079,84	877,92	1.060,52 ± 173,50
Ganho de peso diário (g.dia^{-1})	2,31	2,18	2,04	2,18 ± 0,14
Mortalidade (%)	22,46	22,73	28,48	24,56 ± 3,40
Conversão alimentar aparente	1,25	1,61	1,33	1,40 ± 0,19
Taxa de eficiência alimentar (%)	0,80	0,62	0,75	0,72 ± 0,09
Taxa de crescimento específico (%)	1,36	1,34	1,32	1,34 ± 0,02
Valor da ração (R$.kg^{-1})	3,15	3,13	3,17	3,15 ± 0,02
Produtividade (kg.m^{-3})	61,19	53,99	43,90	53,03 ± 8,69

UFPs = Unidades familiares de produção.

Em relação ao uso dos recursos hídricos, observou que a taxa de renovação de água nas UFPs foi de 2,13 m³ de água por quilograma de peixe produzido, valor 58% superior ao registrado em sistemas familiares de produção com tanques elevados de concreto na África do Sul, onde, devido à escassez hídrica, a renovação total ocorre apenas duas vezes por semana, com relação média de 1,35 m³.kg^{-1} (FAO, 2025).

A taxa média de mortalidade (%) observada nas UFPs foi de 24,56±3,40 (Tabela 2), valor superior à referência de 10% reportada para sistemas com ciclos produtivos entre seis e oito meses (DAFF, 2018; FAO, 2025), porém 23,44% inferior à registrada pela FAO (2025) para sistemas familiares com ciclo de 12 meses, cuja mortalidade média foi de 48% em viveiros escavados. Essa diferença demonstra que, embora as UFPs apresentem menor eficiência zootécnica em relação aos sistemas comerciais de curto e médio prazo, seu desempenho produtivo foi superior ao ciclo de 12 meses (FAO, 2025).

A conversão alimentar aparente (CAA) variou entre 1,25:1 e 1,66:1, com média de 1,40:1 nas UFPs (Tabela 2), valor próximo ao relatado por DAFF (2018) para a espécie em sistemas de produção em fluxo contínuo (1,30:1). Essa média se manteve dentro da faixa ideal de 0,90:1 a 1,80:1 descrita por Kubitza (2004) para cultivos de peixes. A eficiência alimentar observada nas UFPs está diretamente relacionada a fatores como o teor de proteína bruta (PB) da dieta, a frequência alimentar, o fotoperíodo e homogeneidade dos lotes, aspectos determinantes para maximizar o ganho de peso e reduzir o tempo de cultivo (HOSSAIN, 2001; LEWANDOWSKI, 2013; FAO, 2023; LANGI, 2024; FAO, 2025).

Os peixes foram alimentados com ração comercial extrusada para onívoro 42% de PB até o segundo mês de produção, aproximadamente 150 g.peixe^{-1}, concentração condizente com a faixa recomendada de 40% a 50% de PB para alevinos da espécie (LEWANDOWSKI, 2013; FAO, 2023; LANGI, 2024; FAO, 2025). Estudos de Hossain et al. (2001) demonstram que o fornecimento de alimento no período noturno e maior frequência alimentar para alevinos de *C. gariepinus* resulta em melhor conversão alimentar, maior ganho de peso e redução do desperdício de ração.

Do segundo mês (T_2) até a despesca (T_{12}), foi fornecida ração comercial extrusada para onívoro com 35% de proteína bruta (PB), valor que se encontra dentro da faixa recomendada por Langi (2024), entre 30% e 40% de PB. De acordo com a FAO (2025), as melhores taxas de crescimento e conversão alimentar em *Clarias gariepinus* são obtidas com dietas contendo entre 35% e 42% de proteína bruta, evidenciando que o nível de proteína adotado nas UFPs foi adequado às exigências mínimas para produção da espécie.

A frequência alimentar foi realizada 4 vezes.dia^{-1} até o segundo mês (T_0 e T_2) e 3 vezes.dia^{-1} ao longo do ciclo de produção (T_2 – T_{12}). Entretanto, em sistemas com maior densidade de estocagem para a espécie, recomenda-se o aumento da

frequência alimentar, de modo a evitar competição excessiva por alimento, o canibalismo, e melhorar o aproveitamento da ração (HOSSAIN, 2001; FAO, 2025). De acordo com a FAO (2025), a frequência alimentar ideal é entre 5 e 6 vezes.dia^{-1} para peixes até 150g e 2 e 5 vezes.dia^{-1} para adultos, produzidos em sistema com fluxo contínuo de água e alto adensamento de peixes, associada à despesca seletiva periódica dos indivíduos de maior porte, prática que favorece a homogeneidade de crescimento e reduz comportamentos agressivos (HECHT; BRITZ, 1988; FAO, 2025).

Os peixes foram introduzidos no sistema (T_0) com aproximadamente 6 g.peixe^{-1} e o peso médio final foi 794,00±50,00 g.peixe^{-1} nas UFPs (Figura 20). Entre os períodos T_2 e T_8, foi observada em determinadas UFPs e períodos de produção, excesso de ração na água após a saciedade aparente dos peixes (regime *ad libitum*). Já entre T_8 ao T_{12} foi observada a escassez de ração em algumas unidades, situação na qual os produtores complementaram a alimentação dos peixes com subprodutos agroecológicos disponíveis na propriedade, tais como sobras e cascas de banana, folhas de mamona, folhas de abóbora e lentilha-d'água (*Lemna minor*), Assim, a elevação pontual da CAA em algumas UFPs pode estar associada à substituição parcial da ração comercial por alimentos alternativos da propriedade no final do ciclo, visto que mudanças na composição da dieta impactam diretamente a eficiência de conversão alimentar. (HOSSAIN, 2001; LEWANDOWSKI, 2013; FAO, 2023; LANGI, 2024; FAO, 2025).

Na biometria inicial (T_4), correspondente ao quarto mês de cultivo, foi observada a heterogeneidade no crescimento dos lotes entre as três UFPs, condição que se manteve até a biometria final (T_{12}), realizada no momento da despesca (Figura 20). Nessa etapa, foi registrada ampla variação no peso individual, com valores compreendidos entre 300 g e 1.400 g peixe^{-1} em todas as UFPs avaliadas. Dessa maneira, os peixes com peso individual até 850 g foram comercializados para indústria de processamento de pescado e acima de 1.000g para pesque-pague.

Nas UFPs avaliadas, não foi realizada a separação dos exemplarem maiores durante o ciclo de produção, uma vez que cada propriedade dispunha de apenas um tanque de cultivo. A ausência do manejo adequado para a espécie contribuiu para a desuniformidade no lote de produção nas UFPs e possivelmente a ocorrência de canibalismo na fase inicial e mortalidade durante o ciclo de produção, fatores amplamente reconhecidos por comprometerem o desempenho zootécnico e a taxa de

sobrevivência da espécie, principalmente na fase inicial da engorda (HOSSAIN et al., 2001; FAO, 2025).

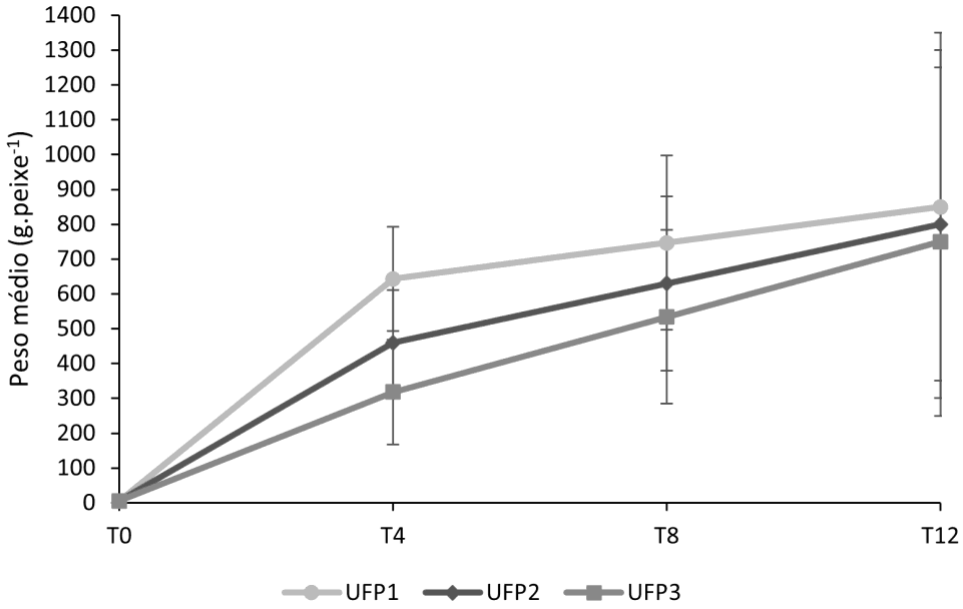


Figura 20. Peso médio de *C. gariepinus* ao longo do ciclo de produção em três UFPs (T_0 – T_{12}). Unidade Familiar de Produção (UFP); Introdução dos peixes (T0); quatro meses (T4); oito meses (T8); despesca (T12).

Durante o ciclo produtivo, foi observada ampla variação nos parâmetros físico-químicos do efluente e no desempenho zootécnico nas três UFPs. Essas oscilações possivelmente estiveram associadas à sazonalidade climática, especialmente à maior amplitude térmica da água entre os períodos de verão e inverno, fator que pode influenciar diretamente o metabolismo dos peixes, o consumo alimentar e, consequentemente, os indicadores de desempenho produtivo. A ausência de manejo adequado para *Clarias gariepinus* contribuiu para a heterogeneidade entre os lotes de peixes, além de favorecer o acúmulo progressivo de matéria orgânica na água, proveniente tanto do fornecimento excessivo de ração quanto da excreção dos animais.

Embora a espécie apresente elevada tolerância a variações nos parâmetros de qualidade da água, como oxigênio dissolvido, amônia e pH (OKOMODA et al., 2019), condições extremas podem comprometer o desempenho produtivo. Entretanto, estudos têm demonstrado que, mesmo em faixas consideradas subótimas de qualidade da água, o manejo alimentar e operacional exerce influência mais significativa sobre o crescimento, a conversão alimentar e o bem-estar da espécie

(FAO, 2025; HILDEBRAND et al., 2025). Assim, práticas adequadas de manejo, especialmente em sistemas de cultivo sem recirculação e com alta densidade de estocagem, constituem fatores determinantes para a manutenção do desempenho zootécnico de *C. gariepinus.*

4.3. Potencial de produção e mercado de Lentilha d'água

Ao longo do período de produção de *Clarias gariepinus*, observou-se um aumento gradual na taxa relativa de crescimento (RGR) da biomassa fresca de *Lemna minor*, atingindo 0,98 %.dia^{-1} em relação à biomassa inicial de 15 g nos tanques de decantação (Capítulo II). Nas Unidades Familiares de Produção (UFPs), o rendimento médio foi de aproximadamente 1,89 kg.m^{-2}.mês^{-1} (62,5 g.m^{-2}.dia^{-1}) de biomassa fresca de *L. minor*, totalizando 136,08 kg ao longo de 12 meses de produção nas três UFPs avaliadas.

O processamento da biomassa em laboratório apresentou rendimento médio de 4% de matéria seca em relação à biomassa fresca, totalizando 5,44 kg.safra^{-1} de matéria-prima seca em pó, o que corresponde a uma produtividade de 2,52 g.m^{-2}.dia^{-1} (peso seco), considerando o total obtido nas três UFPs.

A produção de biomassa fresca de *L. minor* e a fitorremediação do efluente de peixes estão relacionadas à área de cultivo da lentilha d'água (m²) e ao potencial de remoção do fosfato no efluente (HEITZMAN et al., 2024). Nos sistemas de Aquicultura Integrada Multitrófica (AIMT) nas três UFPs avaliadas, estimou-se que seria necessária uma área de 9.498 m², (≈ 1 ha), destinada ao cultivo de *L. minor* para remover o fosfato do efluente (HEITZMAN et al, 2024), considerando a profundidade da lâmina d'água variando entre 5 e 10cm (COUGHLAN et al., 2022; UJONG et al., 2025). Nessa condição, a produção estimada de biomassa seria de 226.800 kg.ha^{-1}.safra^{-1} (peso úmido), equivalente a 9.072 kg.ha^{-1}.safra^{-1} de matéria-prima seca em pó, valores que representam produtividade 2,55 e 1,87 vezes superiores às obtidas em cultivos de soja e milho, respectivamente (CHEN et al., 2018; EMBRAPA, 2025).

No mercado nacional, a comercialização da lentilha-d'água (*Lemna minor*) está principalmente associada ao setor de aquarismo, sendo utilizada como alimento natural e ornamental em sistemas aquáticos. A produção de biomassa fresca ocorre em pequena escala, conduzida por produtores que adotam o modelo de comercialização B2C (*Business-to-Consumer*) por meio de plataformas digitais. Esse formato de venda direta ao consumidor final favorece a obtenção de alto valor

agregado, com preços que podem alcançar R$ 40,00 por 10g de biomassa fresca, devido à venda em pequenos volumes e à demanda específica desse nicho de mercado.

O mercado global de lentilha d'água está avaliado em aproximadamente US$ 89,4 milhões em 2025, com projeção de crescimento para US$ 256,7 milhões até 2035, o que representa uma taxa média anual composta (CAGR) de 11,2% (FMI – *Future Market Insights*, 2025). Cerca de 48,6% dessa demanda corresponde à utilização da matéria-prima na formulação de rações para animais terrestres e organismos aquáticos (FMI, 2025). O preço médio da matéria-prima seca em pó destinada a comercialização B2B (*Business-to-Business*) ao setor agrícola varia entre 200 e 700 USD.t^{-1}, dependendo da finalidade de aplicação, do teor proteico e das concentrações de aminoácidos essenciais presentes no produto (HADAS et al., 2024; SONG et al., 2025).

A biomassa seca em pó de *L. minor* obtida a partir do efluente de produção de peixes no mesmo sistema AIMT apresentou valor médio de 35% de PB e altas concentrações de ácidos graxos essenciais, minerais e pigmentos, com potencial nutricional para o setor de *plant-based food human* e nutrição animal (HEITZMAN et al., 2024). O aproveitamento da biomassa em pó proveniente de efluentes aquícolas como matéria-prima para o setor *plant-based food human* requer avaliação criteriosa quanto aos aspectos de segurança sanitária e qualidade química do material (EFSA, 2021; EFSA, 2022). Essa necessidade decorre da capacidade da lentilha d'água em bioacumular metais pesados, microcontaminantes e microrganismos patogênicos presentes no ambiente aquático (XU et al., 2021; EFSA, 2021; EFSA, 2022).

Para aplicações destinadas à formulação de produtos com elevado grau de exigência sanitária, como os voltados ao consumo humano, empregam sistemas de cultivo em soluções nutritivas controladas (EFSA, 2021; EFSA, 2022), utilizando plantas provenientes de estoques estéreis mantidos *in vitro* e cultivadas em meios aquosos livres de contaminantes, assegurando a rastreabilidade, padronização e conformidade com os padrões internacionais de segurança alimentar definidos por agências regulatórias como a *European Food Safety Authority* – EFSA.

Apesar do reconhecido potencial de produção de biomassa de lentilha d'água gerada a partir da fitorremediação (PIRES et al., 2003; MOHEDANO, 2004; TAVARES, 2004; GRAEFF et al., 2007; OLIVEIRA 2013; GARCIA, 2015; FABONETE et al., 2019; CIRQUEIRA, 2021), sua aplicação direta como ingrediente alimentar

humano, quando oriunda de efluentes, não é recomendada (EFSA, 2021; EFSA, 2022). No entanto, sua utilização no setor agropecuário é tecnicamente viável e ambientalmente vantajosa, pois a lentilha d'água é utilizada para a fitorremediação de efluentes de suinocultura, avicultura e aquicultura, bem como como fonte proteica de elevada digestibilidade e composição nutricional equilibrada (EL-SHAFAI et al., 2004; RIGUEIRA et al., 2021; XU et al., 2021; SOSA et al., 2024; MOUTINHO et al., 2025).

A matéria-prima em pó obtida a partir de efluentes tratados pode apresentar teores proteicos superiores a 30% da matéria seca e concentrações de metais pesados abaixo dos limites estabelecidos para rações animais (EL-SHAFAI et al., 2004; WANG et al., 2021; EFSA, 2021). Essa biomassa apresenta potencial multifuncional, podendo ser direcionada à formulação de rações balanceadas, à síntese de biocombustíveis, à produção de biofertilizantes e ao desenvolvimento de biodefensivos agrícolas (ZHAO et al., 2012; NEGASSA, 2021; SOSA et al., 2024; YAEKASHI; OTA, 2024). Dessa forma, a biomassa de lentilha-d'água configura-se como um produto estratégico na transição para sistemas circulares e ambientalmente sustentáveis de produção aquícola, uma vez que seu aproveitamento em cadeias produtivas integradas representa uma alternativa promissora para a geração de insumos de base biológica, promovendo simultaneamente a fitorremediação dos efluentes e a consolidação de modelos produtivos sustentáveis.

4.4. Pacote tecnológico do sistema AIMT

A produção de peixes em sistemas de aquicultura familiar pode ser conduzida em dois modelos produtivos distintos: o sistema convencional (Sistema 1 – SI) e o sistema AIMT (Sistema 2 – SII) o qual contribui com serviços ecossistêmicos (Figura 21). No Sistema 1, a produção de *Clarias gariepinus* ocorre de forma isolada, com descarte inadequado do efluente e comercialização restrita ao peixe vivo. No Sistema 2, a integração trófica permite o cultivo simultâneo de *C. gariepinus* e *Lemna minor*, promovendo o aproveitamento eficiente do efluente líquido gerado na produção de peixes.

A biomassa fresca de *L. minor* (Produto – P), obtida a partir da fitorremediação do efluente da produção de peixe nos tanques de decantação, pode ser utilizada como alimento natural para animais na propriedade, conforme recomendado pela FAO (2025), ou processada para a obtenção da matéria-prima seca em pó (HEITZMAN et al., 2024), comercializável para os setores agrícolas e biotecnológicos (P). Entre suas

aplicações destacam-se a formulação de rações, produção de biofertilizantes, biodefensivos agrícolas e biocombustíveis, com foco no mercado de insumos (CHEN et al., 2018; FALAYE et al., 2022; SOSA et al., 2024; THONGTHUNG et al., 2024; YAEKASHI, 2024; SONG et al., 2025).

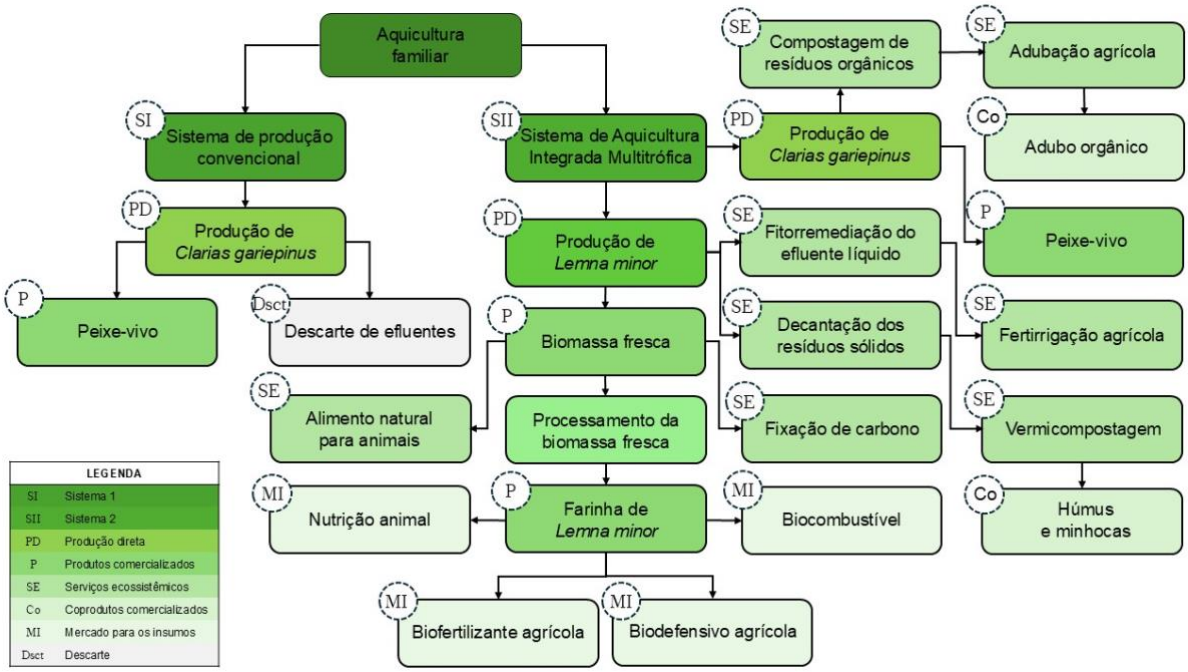


Figura 21. Integração trófica e circularidade produtiva na aquicultura familiar: comparação entre sistemas convencionais e AIMT.

O sistema AIMT proporciona diversos SE, incluindo a fitorremediação de efluentes, a decantação de resíduos sólidos, a fixação de carbono, a fertirrigação, bem como processos de vermicompostagem e compostagem orgânica utilizando carcaça de peixes. Os coprodutos (Co) resultantes desses serviços ecossistêmicos podem ser comercializados ou reaproveitados nas UFPs, contribuindo para o incremento da renda familiar rural e/ou para a redução dos custos de insumos, como adubos orgânicos, húmus de minhoca e biomassa de minhocas (Coprodutos – Co).

Dessa forma, a integração entre a produção de *C. gariepinus* e *L. minor* não apenas eleva a produtividade e o valor agregado da biomassa gerada, mas também reforça a sustentabilidade ambiental e econômica das UFPs, promovendo a economia circular e ampliando o potencial de comercialização de produtos de base biológica com valor agregado.

4.5. Viabilidade econômica dos sistemas de produção

A implantação do Sistema Convencional (SI) demanda um capital fixo de R$ 6.190,00, enquanto o Sistema de Aquicultura Integrada Multitrófica (SII) exige um investimento 84,7% superior (R$ 11.432,00), devido à necessidade de infraestrutura (I), e equipamentos e materiais (EM) complementares (Tabela 3). Em ambos os sistemas, é necessária a instalação de ao menos dois tanques elevados de 20 m³ destinados ao cultivo de *Clarias gariepinus*, garantindo o manejo adequado da espécie. Essa configuração permite a separação dos peixes por tamanho, maiores e menores, a cada dois meses, promovendo maior homogeneidade dos lotes e reduzindo o tempo total de cultivo de 12 para 8 meses, o que contribui para melhores ganhos produtivos, econômicos e para o aproveitamento da infraestrutura disponível.

No Sistema AIMT (SII), o investimento em infraestrutura (I) totaliza R$ 9.492,00, 81% superior ao SI (R$ 5.250,00), para a incorporação de tanques adicionais de polietileno (500 L), kits de compostagem doméstica e bombonas para coleta de resíduos sólidos (Tabela 4). Em equipamentos e materiais (EM), o SI demanda um investimento de R$ 940,00, e o SII, de R$ 1.940,00, devido à aquisição de itens adicionais, como equipamentos de Proteção Individual (EPI agrícola) e materiais específicos para o manejo integrado. A depreciação total estimada do Sistema AIMT também é superior à do Sistema Convencional, R$ 1.798,53 e R$ 916,48, respectivamente.

A maior demanda por capital fixo no Sistema de Aquicultura Integrada Multitrófica (AIMT) está associada ao pacote tecnológico adotado, que inclui instalações complementares destinadas aos processos de tratamento e reaproveitamento de resíduos provenientes da atividade aquícola. Esse conjunto tecnológico contempla a implantação de um sistema de decantação com fitorremediação por *Lemna minor*, responsável pela redução dos compostos nitrogenados presentes nos efluentes da produção de peixes (HEITZMAN et al., 2024).

Integra-se também a vermicompostagem, que utiliza a minhoca *Eisenia fetida* na ciclagem dos compostos nitrogenados provenientes da decantação dos resíduos sólidos do efluente, convertendo-os em húmus (COSTA JÚNIOR et al. 2020; SILVA; TERAMOTO, 2023). Ademais, o pacote tecnológico do sistema prevê o reaproveitamento das carcaças de peixes mortos, incorporando-as ao processo de

produção de adubo orgânico (LOPES, 2020), o que contribui para o ciclo de reaproveitamento dos resíduos do sistema convencional e para o fortalecimento da sustentabilidade ambiental e produtiva do sistema nas UFPs.

Para a implantação do sistema de decantação, adota-se a proporção de 2:1, ou seja, dois tanques de 500 L contendo 1m² de lâmina d'água com *Lemna minor* para cada tanque de 20 m³ destinado ao cultivo de peixes, com o objetivo de promover a fitorremediação e a decantação dos resíduos sólidos após 30 dias, resultando na formação do lodo proveniente da piscicultura e produção de biomassa úmida *L. minor* (1,89 $kg.m^{-2}.mês^{-1}$) (HEITZMAN et al., 2024). Dessa maneira, são necessários quatro tanques de 500 L no sistema AIMT, totalizando R$ 1.000,00 (Tabela 4).

Os resíduos sólidos gerados no sistema de decantação das UFPs são coletados bimestralmente e apresentam elevado potencial de reaproveitamento como insumo para processos de vermicompostagem (SILVA; TERAMOTO, 2023). Costa Júnior et al. (2020) observaram melhor desempenho na produção da minhoca *Eisenia fetida* quando utilizado o lodo proveniente da criação de *Clarias gariepinus* com serragem de eucalipto (*Eucalípitus sp.*) como substrato na proporção 1:1, evidenciando o potencial produtivo dos resíduos aquícolas no reaproveitamento sustentável dentro do sistema AIMT.

Silva e Teramoto (2023) constataram que, no mesmo sistema de produção de *C. gariepinus* em UFPs, é possível obter, em média, 130 L de húmus de minhoca e 7.400 unidades de minhocas por bimestre. Dessa maneira, é necessário utilizar 4 bombonas de 100 L com tampas removíveis para o armazenamento do resíduo sólido e incremento de serragem gerado nos tanques de decantação e 4 kits de composteira para vermicompostagem para produção de húmus, totalizando R$ 3.292,00 de custo fixo em infraestrutura para a vermicompostagem (Tabela 4).

A compostagem orgânica das carcaças de peixes provenientes de mortalidades ao longo do ciclo produtivo representa uma alternativa eficiente para o manejo sustentável desses resíduos na piscicultura. Além de reduzir impactos ambientais associados ao descarte inadequado, esse processo permite a conversão dos resíduos em adubo orgânico, que pode ser utilizado nas próprias UPFs ou comercializado, agregando valor ao sistema produtivo e fortalecendo a sustentabilidade econômica da atividade. Conforme descrito por Lopes (2020), a compostagem realizada com carcaças de peixes associadas à serragem de eucalipto

(*Eucalyptus sp*.), na proporção de 0,5:1, em sistema de recarga contínua, apresenta rendimento médio de aproximadamente 50% de adubo orgânico ao final do processo.

Outro aspecto relevante é a possibilidade de implementar essa prática utilizando estruturas já existentes nas propriedades rurais destinadas à compostagem coberta, o que reduz os custos de implantação e facilita sua adoção por produtores familiares. Nesse contexto, para viabilizar, operacionalmente, essa prática nas UPFs avaliadas, foram considerados, no componente de equipamentos e materiais (EM), os itens necessários ao manejo do processo, incluindo equipamentos de proteção individual (EPIs) e utensílios auxiliares, como pás, rastelos e lonas, totalizando um investimento estimado de R$ 1.000,00 (Tabela 3).

O custo total (CG) do Sistema Convencional (SI) é de R$ 25.941,18, enquanto o do Sistema de Aquicultura Integrada Multitrófica (SII) atinge R$ 33.094,73 (Tabela 5), o que representa um acréscimo aproximado de 27,5%. No SI, o custo total por safra de oito meses é composto por R$ 22.200,00 em custos variáveis (CV) e R$ 3.741,18 em custos fixos (CF). Já no SII, o custo total por safra corresponde a R$ 26.680,00 em custos variáveis e R$ 6.414,73 em custos fixos, o que reflete um incremento aproximado de 28% em relação ao sistema convencional.

Tabela 3. Capital fixo para a Implantação do Sistema Convencional (SI) e Sistema de AIMT (SII) nas UFPs.

Itens	Quant. (unid.)	Valor Unit. (R$)	Valor Total (R$)	SU (%.valor^{-1})	VS (R$)	VU (anos)	D (R$)
(SI) Sistema Convencional							
(A) Infraestrutura (I)			**R$ 5.250,00**		**R$ 51,25**		**R$ 519,88**
Tanque circular de geomembrana - PEAD 20m³	2	R$ 2.000,00	R$ 4.000,00	10%	R$ 40,00	10	R$ 396,00
Bomba d'água	1	R$ 700,00	R$ 1.000,00	10%	R$ 10,00	10	R$ 99,00
Diversos (Canos, conexões, outros)	1	R$ 250,00	R$ 250,00	5%	R$ 1,25	10	R$ 24,88
(B) Equipamentos e materiais (EM)			**R$ 940,00**		**R$ 39,93**		**R$ 396,60**
Kit completo de análise de água	1	R$ 600,00	R$ 600,00	10%	R$ 12,00	2	R$ 285,00
Passaguá "*Fishing net*"	2	R$ 80,00	R$ 160,00	10%	R$ 5,33	3	R$ 51,56
Balança de campo digital	2	R$ 30,00	R$ 60,00	10%	R$ 3,00	2	R$ 28,50
Ictiômetro	2	R$ 30,00	R$ 60,00	5%	R$ 1,00	3	R$ 19,67
Sacolas para transporte de peixe	2	R$ 30,00	R$ 60,00	5%	R$ 0,60	5	R$ 11,88
(SII) Sistema de Aquicultura Integrada Multitrófica							
(A) Infraestrutura (I)			**R$ 9.492,00**		**R$ 59,50**		**R$ 1.138,60**
Tanque circular de geomembrana - PEAD 20m³	2	R$ 2.000,00	R$ 4.000,00	10%	R$ 40,00	10	R$ 396,00
Bomba d'água	1	R$ 700,00	R$ 1.000,00	10%	R$ 10,00	10	R$ 99,00
Tanque circular de 500L de Polietileno	4	R$ 250,00	R$ 1.000,00	10%	R$ 10,00	10	R$ 99,00
Diversos (Canos, conexões, outros)	2	R$ 250,00	R$ 500,00	5%	R$ 2,50	10	R$ 49,75
Kit composteira doméstica 120L	4	R$ 500,00	R$ 2.000,00	5%	R$ 20,00	5	R$ 396,00
Bombona 100L com tampa removível	4	R$ 323,00	R$ 1.292,00	5%	R$ 6,46	10	R$ 128,55
(B) Equipamentos e materiais (EM)			**R$ 1.940,00**		**R$ 39,93**		**R$ 659,49**
Kit completo de análise de água	1	R$ 600,00	R$ 600,00	10%	R$ 12,00	5	R$ 117,60
Passaguá	2	R$ 80,00	R$ 160,00	10%	R$ 5,33	3	R$ 51,56
Balança de campo digital	2	R$ 30,00	R$ 60,00	10%	R$ 3,00	2	R$ 28,50
Ictiômetro	2	R$ 30,00	R$ 60,00	5%	R$ 1,00	3	R$ 19,67
Sacolas para transporte de peixe	2	R$ 30,00	R$ 60,00	5%	R$ 0,60	5	R$ 11,88
EPI Agrícola	2	R$ 250,00	R$ 500,00	5%	R$ 8,33	3	R$ 163,89
Outros	1	R$ 500,00	R$ 500,00	5%	R$ 5,00	5	R$ 99,00
Capital Fixo SI							**R$ 6.190,00**
Capital Fixo SII							**R$ 11.432,00**

SU: Sucateamento (%.valor^{-1}); VS: Valor de sucata (R$); VU: Vida útil (anos); D: Depreciação (R$).

Ambos os sistemas apresentam valores semelhantes no que se refere a produção de peixe, como a aquisição de ração, alevinos, custos de mão de obra para a despesca, entre outros (Tabela 4). Entretanto, o Sistema AIMT (SII) apresenta aumento de 100% no custo com assistência técnica especializada, devido à maior complexidade operacional e ao maior conhecimento multidisciplinar necessários ao manejo adequado dos diferentes componentes biológicos e produtivos envolvidos. O SII incorpora itens específicos nos custos variáveis, como a serragem de eucalipto (*Eucalyptus sp.*), a biomassa úmida de *Lemna minor* e o reaproveitamento de carcaças de peixes, insumos diretamente associados às práticas de reaproveitamento e ciclagem de resíduos aquícolas.

Em relação aos custos fixos (CF), o SII apresenta valores superiores (R$ 6.414,73) em comparação com o SI (R$ 3.741,18). Esse aumento decorre, principalmente, da maior depreciação dos equipamentos e do acréscimo nas horas de pró-labore do produtor rural, de 40 h.mês^{-1} no SI para 80 h.mês^{-1} no SII, refletindo o tempo adicional demandado pelas atividades de manejo associadas aos diferentes serviços ecossistêmicos que estão diretamente relacionado à expansão das etapas produtivas e à adoção de um pacote tecnológico mais abrangente, que incorpora processos de tratamento, reaproveitamento e transformação de resíduos provenientes da atividade aquícola.

Tabela 4. Custo total dos desembolsos com os SI e SII nas UFPs durante a produção de *Clarias gariepinus* e *Lemna minor*.

Itens	Unidade	Quant.	Valor Unit. (R$.mês^{-1})	Meses (nº)	Valor Total (R$.safra^{-1})
(SI) Sistema Convencional					
(A) Custos Variáveis (CV)					**R$ 22.200,00**
Alevinos de *Clarias gariepinus*	milheiro	4,4	R$ 375,00	1	R$ 1.650,00
Ração 42% de PB	sacos	4	R$ 200,00	1	R$ 800,00
Ração 32% de PB	sacos	140	R$ 110,00	1	R$ 15.400,00
Outros	-	1	R$ 200,00	1	R$ 200,00
Despesca	unid.	5	R$ 50,00	1	R$ 250,00
Assistência técnica especializada	horas	2	R$ 250,00	8	R$ 4.000,00
(B) Custos Fixos (CF)					**R$ 3.741,18**
Depreciação	-	1	R$ 91,65	8	R$ 733,18
Energia Elétrica	kwh	1	R$ 100,00	8	R$ 800,00
Pró-Labore	horas	40	R$ 6,90	8	R$ 2.208,00
(SII) Sistema de Aquicultura Integrada Multitrófica					
(A) Custos Variáveis (CV)					**R$ 26.680,00**
Alevinos de *Clarias gariepinus*	milheiro	4,4	R$ 375,00	1	R$ 1.650,00
Ração 42% de PB	sacos	4	R$ 200,00	1	R$ 800,00
Ração 32% de PB	sacos	140	R$ 110,00	1	R$ 15.400,00
Outros	-	1	R$ 200,00	1	R$ 200,00
Despesca	unid.	5	R$ 50,00	1	R$ 250,00
Assistência técnica especializada	horas	4	R$ 250,00	8	R$ 8.000,00
Serragem de Eucalipito (*Eucalípitus sp.*)	ton.	1	R$ 350,00	1	R$ 350,00
Lentilha d'água (*Lemna minor*)	unid.	1	R$ 30,00	1	R$ 30,00
Carcaça de peixe	kg	250	-	-	-
(B) Custos Fixos (CF)					**R$ 6.414,73**
Depreciação	-	1	R$ 149,84	8	R$ 1.198,73
Energia Elétrica	kwh	1	R$ 100,00	8	R$ 800,00
Pró-Labore	horas	80	R$ 6,90	8	R$ 4.416,00
Custo total (CG) SI					**R$ 25.941,18**
Custo total (CG) SII					**R$ 33.094,73**

A receita bruta (RB) obtida no Sistema Convencional (SI) é de R$ 31.680,00.safra^{-1} (8 meses), proveniente exclusivamente da comercialização do peixe-vivo (*Clarias gariepinus*), com produção total de 3.960 kg e valor unitário de R$ 8,00.kg^{-1} (Tabela 6)(Tabela 7). No Sistema de Aquicultura Integrada Multitrófica (SII), a receita bruta totaliza R$ 64.430,00.safra^{-1}, representando um incremento de aproximadamente 103% em relação ao modelo convencional.

A biomassa fresca de lentilha-d'água (*Lemna minor*), proveniente do processo de fitorremediação do efluente da produção de peixes, pode ser comercializada ensacada ou acondicionada em potes vedados contendo o próprio efluente aquícola, o que favorece a sobrevivência e a viabilidade fisiológica da espécie durante o transporte até o consumidor final. O produto apresenta um valor médio de R$ 10,00 por 50 g, totalizando R$ 200,00.kg^{-1} (Tabela 5), configurando-se como um insumo de elevado valor agregado e com potencial de nicho nos mercados voltados ao aquarismo, à alimentação animal e aos sistemas de produção sustentáveis. Considerando uma área de apenas 4 m² de lâmina d'água nas UFPs, a comercialização da biomassa pode gerar uma receita total estimada de R$ 12.000,00.safra^{-1}, evidenciando o alto rendimento econômico em pequena escala.

O adubo orgânico, produzido a partir do reaproveitamento de carcaças de peixes, apresenta um valor médio de R$ 5,00.kg^{-1}, sendo comercializado em pacotes de 5 kg ao preço de R$ 25,00. Esse produto constitui uma alternativa sustentável para o manejo dos resíduos aquícolas, promovendo a ciclagem de nutrientes e a geração de valor no sistema produtivo. Considerando uma mortalidade média de 10% na produção de peixes nas Unidades Familiares de Produção (UFPs), é possível obter cerca de 200 kg de adubo orgânico final por safra, resultando em uma receita total estimada de R$ 1.000,00.safra^{-1}.

O húmus de minhoca, comercializado como adubo orgânico natural, tem valor médio de R$ 5,00.kg^{-1}, sendo usualmente vendido em pacotes de 5 kg ao preço de R$ 25,00. Considerando a produção de 130 L de húmus a partir do efluente sólido do sistema de decantação, oriundo da produção de peixes em tanque de 20 m³ (SILVA; TERAMOTO, 2023), é possível gerar aproximadamente 1.040 kg de húmus por safra, resultando em receita estimada de R$ 5.200,00 (Tabela 5). Esse produto agrega valor ambiental e econômico ao sistema, promovendo o reaproveitamento eficiente do efluente sólido, contribuindo para a sustentabilidade do modelo produtivo.

A comercialização de minhocas (*Eisenia fetida*) pode ocorrer de duas formas distintas: associada ao húmus, para uso na alimentação animal e em processos de compostagem, e como isca-viva destinada ao setor de pesca esportiva. O valor unitário da *Eisenia fetida*, conhecida popularmente como minhoca californiana, varia entre R$ 0,25 e R$ 0,50 por unidade. Considerando uma produção média de 7.400 unidades a cada dois meses nas UFPs (SILVA; TERAMOTO, 2023), é possível alcançar aproximadamente 59.200 unidades por safra (≈ 59,2 kg.safra^{-1}), o que

representa uma receita estimada de R$ 14.800,00.safra^{-1} (R$ 0,25un.). Esse produto reforça o potencial econômico e ecológico do sistema multitrófico, agregando valor aos coprodutos da aquicultura familiar.

Os produtos e coprodutos gerados no Sistema de Aquicultura Integrada Multitrófica (SII) apresentam alto potencial de comercialização em plataformas digitais, lojas agropecuárias, feiras livres municipais e eventos de agronegócios. Esses canais de venda favorecem a diversificação de mercados, ampliam a visibilidade dos produtos sustentáveis e contribuem para a inclusão socioeconômica das UFPs.

Tabela 5. Receitas do sistema convencional (SI) e sistema AIMT (SII) realizadas em Unidades Familiares de Produção (UFPs) no bioma da Mata Atlântica, Vale do Ribeira, São Paulo.

Produção (Q)	Quant. (kg)	Valor Unit. (R$.kg^{-1})	Valor Total (R$.safra^{-1})
(SI) Sistema Convencional			**R$ 31.680,00**
(P1) Peixe-vivo (*Clarias gariepinus*)	3.960,00	R$ 8,00	R$ 31.680,00
(SII) Sistema de Aquicultura Integrada Multitrófica			**R$ 53.587,20**
(P1) Peixe-vivo (*Clarias gariepinus*)	3.960,00	R$ 8,00	R$ 31.680,00
(P2) Biomassa fresca (*Lemna minor*)	60,00	R$ 200,00	R$ 12.000,00
(Co1) Adubo orgânico	200,00	R$ 5,00	R$ 1.000,00
(Co2) Húmus de minhoca	1.040,00	R$ 5,00	R$ 5.200,00
(Co3) Minhoca (*Eisenia fetida*)	59,20	R$ 250,00	R$ 14.800,00
Receita Bruta SI			**R$ 31.680,00**
Receitas Bruta SII			**R$ 64.430,00**

A análise dos indicadores operacionais (IOP) e lucratividade (IL) (Tabela 6) indicaram a eficiência econômica do Sistema de Aquicultura Integrada Multitrófica (SII) em relação ao Sistema Convencional (SI), refletindo na maior eficiência produtiva e sustentabilidade financeira do pacote tecnológico. O SII apresentou lucro líquido de 445%, superior ao SI, de R$ 31.335,27 e R$ 5.738,82 por safra, respectivamente.

A lucratividade, indica a eficiência econômica do sistema ao relacionar o lucro líquido com a receita total (ENGLE, 2010). Dessa maneira, o SII (AIMT) obteve 49% de lucratividade por safra, enquanto o SI apresentou apenas 18%, demonstrando que, para cada real vendido, o sistema integrado gera quase o triplo de retorno líquido.

No SI, o custo médio do produto gerado (peixe-vivo) foi de R$ 6,55.kg^{-1}, enquanto no SII foi de apenas R$ 0,51.kg^{-1} por safra, com redução superior a 92%. Essa redução é relacionada a integração dos produtos e coprodutos produzidos a partir dos serviços ecossistêmicos inclusos no pacote tecnológico (SII) nas UFPs.

No Sistema AIMT, o resultado líquido foi de R$ 467,49.kg^{-1}.safra^{-1}, contrastando com os R$ 1,45.kg^{-1}.safra^{-1} observados no Sistema Convencional. Essa diferença está relacionada à capacidade do sistema integrado (SII) de promover maior valor agregado por unidade de área, otimizando o espaço produtivo e diversificando a produção, em vez de depender exclusivamente do volume de peixes cultivados, como ocorre no sistema convencional (SI).

O SII apresentou um ponto de equilíbrio de 70,72 kg, enquanto o SI exigiu 3.242,65.kg^{-1} por safra para atingir o mesmo resultado, indicando que são necessários apenas 70,72 kg de produtos e coprodutos (SII) para cobrir todos os custos, sem gerar lucro ou prejuízo nas UFPs em um ciclo de produção. Essa vantagem produtiva é resultante da diversificação de produtos secundários como, biomassa fresca de *Lemna minor* (P2), adubo orgânico (Co1), húmus de minhoca (Co2) e minhocas (Co3) (Tabela 3), associada a utilização do pacote tecnológico integrado, que potencializa a ciclagem de nutrientes, reduz perdas e otimiza o aproveitamento de insumos.

Tabela 6. Indicadores financeiros do Sistema Convencional (SI) e Sistema AIMT (SII) durante a produção de *Clarias gariepinus* e *Lemna minor*.

Indicadores Operacionais (IOP)	**Especificação**	**(SI) SC**	**(SII) AIMT**
Investimento Inicial	R$	R$ 32.131,18	R$ 44.526,73
Capital Fixo	R$	R$ 6.190,00	R$ 11.432,00
Capital de Giro	R$	R$ 25.941,18	R$ 33.094,73
Indicadores de Lucratividade (IL)			
Custos Variáveis	R$.safra^{-1}	R$ 22.200,00	R$ 26.680,00
Custos Fixos	R$. safra^{-1}	R$ 3.741,18	R$ 6.414,73
Custo Total	R$. safra^{-1}	R$ 25.941,18	R$ 33.094,73
Produção Total	kg. safra^{-1}	3.960,00	5.269,20
Receita Bruta	R$. safra^{-1}	R$ 31.680,00	R$ 64.430,00
Lucro Líquido	R$. safra^{-1}	R$ 5.738,82	R$ 31.335,27
Lucratividade	%. safra^{-1}	18%	49%
Custo Médio	R$.kg^{-1}. safra^{-1}	R$ 6,55	R$ 5,10
Resultado Líquido	R$.kg^{-1}. safra^{-1}	R$ 1,45	R$ 4,67
Ponto de Equilíbrio	kg. safra^{-1}	3.242,65	707,20
Indicadores de Viabilidade Econômica (IVE)			
TMA	%.ano^{-1}	16%	16%
TIR	%.ano^{-1}	14%	35%
VPL	R$	R$ 39.773,54	R$ 43.156,85
Payback	anos	6,70	2,32
RCB	R$.R^{-1}	R$ 1,13	R$ 1,67

TMA: Taxa mínima atrativa (%.ano^{-1}); TIR = Taxa interna de retorno (%.ano^{-1}); VPL = Valor presente líquido (R$); RCB: Relação custo-benefício (R$.R^{-1}).

Os indicadores de viabilidade econômica (IVE) corroboram com os resultados encontrados nos indicadores operacionais (IOP) e lucratividade (IL), indicando a eficiência econômica do Sistema AIMT (SII) (Tabela 7). Ambos os sistemas foram avaliados com uma Taxa Mínima de Atratividade (TMA) de 16% ao ano. Entretanto, a Taxa Interna de Retorno (TIR) do SII foi de 35%, o que gera retornos maiores do que o sistema convencional (14% ao ano), demonstrando elevada capacidade de remuneração do capital investido.

O Valor Presente Líquido (VPL) evidencia a eficiência do SII, que alcançou R$ 43.156,85, acima do obtido pelo SI (R$ 39.773,54), demonstrando o elevado potencial do sistema integrado em gerar valor agregado por unidade de área e insumo, por meio da otimização dos recursos e da menor dependência de insumos externos. A Relação Custo-Benefício (RCB) do SII foi de R$ 1,67, superior ao R$ 1,13 observado no SI, indicando que o sistema integrado proporciona maior retorno financeiro para cada real investido, refletindo no melhor aproveitamento dos recursos produtivos e maior sustentabilidade econômica.

Os indicadores financeiros demonstraram que o Sistema de Aquicultura Integrada Multitrófica (SII) apresentou desempenho econômico superior ao do Sistema Convencional (SI) e aos principais referenciais de investimento do mercado financeiro, baseados na taxa Selic e na poupança. O SII atingiu aproximadamente R$ 290.000,00 ao final do décimo ano de simulação, enquanto o SI alcançou cerca de R$ 70.000,00 no mesmo período, demonstrando maior capacidade de geração de valor no médio e no longo prazo. O *Payback* do Sistema AIMT (SII) foi de 2,32 anos, reduzindo em aproximadamente três anos o capital investido em relação ao Sistema Convencional (6,70 anos – SI), o que evidencia uma recuperação mais rápida do capital inicial e menor exposição ao risco financeiro.

O Sistema de Aquicultura Integrada Multitrófica (AIMT) apresentou desempenho econômico e produtivo significativamente superior ao sistema convencional, evidenciando os benefícios inerentes à integração trófica entre a produção de peixe (*Clarias gariepinus*), a lentilha-d'água (*Lemna minor*) e aos processos de ciclagem de nutrientes. Essa integração promove o aproveitamento eficiente dos resíduos metabólicos e sólidos gerados no cultivo, os quais são convertidos em coprodutos de elevado valor agregado (KURNIAWAN et al., 2025), como biomassa vegetal e adubo orgânico (LOPES, 2020; COSTA JÚNIOR et al. 2020; SILVA; TERAMOTO, 2023; HEITZMAN et al., 2024)

A *Lemna minor* torna-se percursora dos serviços ecossistêmicos, atuando como agente fitorremediador na remoção de compostos nitrogenados (amônia, nitrito e nitrato) e fosfatados do efluente, reduzindo a eutrofização e melhorando a qualidade do efluente (HEITZMAN et al., 2024). Além de melhorar o desempenho ambiental do sistema, a biomassa resultante pode ser aproveitada como ingrediente alternativo em rações ou insumo na compostagem (LENG et al., 1995; HEITZMAN et al., 2024), ampliando o valor econômico do ciclo produtivo.

O sistema de decantação, inserido após o tanque de produção de peixes, colabora na sedimentação natural dos sólidos, como fezes e sobras de ração, resultando no lodo retido no fundo do sistema (SILVA; TERAMOTO, 2023). O lodo tradicionalmente considerado resíduo, é transformado em coproduto do sistema AIMT por meio da produção de húmus por meio da vermicompostagem, promovendo a ciclagem de nitrogênio e fósforo (COSTA JÚNIOR et al., 2022; SILVA; TERAMOTO, 2023). A carcaça de peixes descartada é incorporada ao sistema de compostagem, enriquecendo o material orgânico com nitrogênio, cálcio e fósforo, o que favorece a produção de adubos orgânicos de alto valor nutricional (LOPES, 2020; SOSA et al., 2024).

Essa abordagem evidencia a circularidade e sustentabilidade do Sistema AIMT, que reduz perdas, maximiza o uso de recursos internos e gera produtos de valor agregado com potencial de comercialização. Assim, o desempenho econômico superior do sistema AIMT decorre da integração eficiente entre processos ecológicos e produtivos, proveniente do reaproveitamento de resíduos, o que reduz custos operacionais, aumenta a rentabilidade e fortalece a sustentabilidade ambiental, reduzindo as perdas econômicas associadas à monocultura (BISWAS et al., 2020).

5. CONCLUSÕES

A sistematização dos processos produtivos em pequena escala e sua organização em um modelo de tecnologia social demonstraram-se estratégias eficazes para fortalecer a inovação em comunidades rurais. A elaboração de um protocolo de difusão tecnológica permitiu não apenas padronizar as práticas, mas também ampliar sua acessibilidade e potencial de impacto. A análise dos subprodutos animais e vegetais evidenciou um campo promissor para agregação de valor, sobretudo no crescente mercado de alimentos à base de plantas, reforçando a viabilidade econômica e ambiental de modelos produtivos integrados.

A avaliação conjunta dos custos de implementação e operação, dos dados de produção e dos resultados financeiros possibilitou a aplicação de indicadores de eficiência bioeconômica, fornecendo uma base robusta para decisões estratégicas e para a otimização dos sistemas produtivos analisados, com destaque para o Sistema de Aquicultura Integrada Multitrófica (AIMT). Os resultados evidenciam que iniciativas desse tipo podem impulsionar significativamente a competitividade das pequenas propriedades rurais, especialmente quando orientadas pelos princípios da economia circular.

Assim, este estudo amplia as fronteiras da bioeconomia aplicada à aquicultura ao identificar oportunidades concretas para o desenvolvimento de produtos, processos e tecnologias sustentáveis. Ao integrar inovação social, o uso eficiente de recursos e a geração de valor em sistemas produtivos locais, contribui-se para uma transição mais justa, resiliente e sustentável no meio rural, alinhada às demandas contemporâneas por produção responsável e desenvolvimento territorial.

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CONSIDERAÇÕES FINAIS

A presente tese, apresentou uma abordagem integrada para compreender e demonstrar o potencial da macrófita aquática *Lemna minor* como elemento estratégico para o desenvolvimento de sistemas aquícolas mais sustentáveis, integrada com produção de peixe (*Clarias gariepinus*), alinhada aos princípios da bioeconomia e da economia circular. Ao longo dos três capítulos, foram reunidas evidências científicas que conectam o conhecimento básico, a experimentação aplicada e a avaliação bioeconômica, formando uma base consistente para a consolidação de tecnologias sociais voltadas à aquicultura familiar.

O primeiro capítulo contribuiu para a organização e atualização do conhecimento científico sobre *L. minor*, por meio de uma revisão sistemática da literatura, evidenciando seu amplo potencial em áreas como a fitorremediação, a ecotoxicologia, a produção de biomassa e a geração de bioprodutos. Essa síntese permitiu identificar lacunas relevantes na literatura, sobretudo relacionadas à integração entre abordagens moleculares, ecológicas e biotecnológicas, indicando caminhos promissores para o avanço da pesquisa e para a exploração do potencial dessa macrófita em sistemas produtivos baseados na bioeconomia.

No segundo capítulo, os resultados experimentais obtidos em unidades familiares de produção no Vale do Ribeira, no bioma da Mata Atlântica, demonstraram que a integração entre *Clarias gariepinus* e *Lemna minor* em sistemas de aquicultura integrada multitrófica (AIMT) pode contribuir significativamente para a melhoria da qualidade da água, ao promover a remoção de nutrientes e reduzir impactos ambientais associados aos efluentes aquícolas. Além disso, a biomassa produzida apresentou elevada qualidade nutricional e potencial para a geração de novos produtos de valor agregado, como ingredientes para rações, alimentos funcionais e insumos para a bioindústria, reforçando o papel da macrófita como componente-chave em sistemas produtivos circulares.

Por sua vez, o terceiro capítulo evidenciou que a incorporação da *L. minor* nos sistemas produtivos familiares pode gerar benefícios bioeconômicos relevantes, incluindo a diversificação de produtos, o aumento da eficiência do uso de recursos e a geração de coprodutos com potencial de mercado. A análise bioeconômica demonstrou que a integração entre produção animal e vegetal, na lógica da economia

circular, fortalece a resiliência econômica das unidades familiares de produção, contribuindo para o desenvolvimento territorial sustentável e para a valorização das cadeias produtivas locais.

De forma integrada, os resultados desta tese demonstram que a utilização da *Lemna minor* em sistemas de aquicultura familiar representa uma estratégia inovadora capaz de conectar sustentabilidade ambiental, geração de valor econômico e inclusão social. No contexto do Vale do Ribeira — uma região marcada por elevada biodiversidade, mas também por desafios socioeconômicos — a adoção de sistemas produtivos baseados na bioeconomia pode contribuir para fortalecer a segurança alimentar, ampliar oportunidades de renda e promover o uso sustentável dos recursos naturais. Assim, este estudo avança na proposição de um modelo de tecnologia social replicável, capaz de apoiar políticas públicas, programas de extensão e iniciativas de inovação voltadas ao desenvolvimento sustentável da aquicultura familiar no Brasil e em outras regiões tropicais.