UNIVERSIDADE FEDERAL DA GRANDE DOURADOS
Faculdade de Ciências Agrárias
Programa de Pós-Graduação em Zootecnia

IMPACTOS DA COMPLEXIDADE AMBIENTAL E ALIMENTAÇÃO NOS ESTADOS AFETIVOS DE CARACÍDEOS PANTANEIROS

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Dourados - MS
(2026)

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IMPACTOS DA COMPLEXIDADE AMBIENTAL E ALIMENTAÇÃO NOS ESTADOS AFETIVOS DE CARACÍDEOS PANTANEIROS

Leticia Maria Albuquerque Conceição

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BIOGRAFIA DO AUTOR

Leticia Maria Albuquerque Conceição é Médica Veterinária formada pela UFMT campus Sinop (2017–2023). Atualmente atua como veterinária no plantel de peixes ornamentais do Aquário municipal de Cuiabá (MT) e é estudante de pós-graduação em Zootecnia com ênfase em bem-estar animal aplicado a peixes ornamentais de água doce. Atuou à frente de projetos voltados ao comportamento reprodutivo e ao bem-estar de ciclídeos neotropicais. Nascida em Sinop, filha de Vilma Leite Albuquerque e Aparecido Donizeth da Conceição, busca sempre superar desafios e contribuir com o avanço da ciência aplicada ao manejo e conservação de peixes ornamentais

EPÍGRAFE

Não perguntamos para qual propósito útil os pássaros cantam, pois o canto é seu prazer, já que foram criados para cantar. Da mesma forma, não devíamos perguntar por que a mente humana se esforça por penetrar os segredos dos céus [...]. A diversidade dos fenômenos da natureza é tão grande, e os tesouros ocultos nos céus são tão ricos, exatamente para que a mente humana nunca esteja carente de uma renovada nutrição.

Johannes Kepler, Mysterium Cosmographicum.

DEDICATÓRIA

Dedico este trabalho a minha mãe Vilma Leite Albuquerque Conceição, ao meu pai Aparecido Donizeth da Conceição e ao meu irmão Lucas Donizeth Albuquerque Conceição. E a pequena Leticia.

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LISTA DE ABREVIATURAS

PRISMA: *Preferred Reporting Items for Systematic Reviews and Meta-Analyses;*

PICO: População alvo, Intervenção, Controle e *Outcome* (intervenção);

PubMed: Public MEDical literature;

CAPES: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior;

DNA: Deoxyribonucleic Acid (Ácido Desoxirribonucleico);

UFGD: Universidade Federal da Grande Dourados;

°C: Temperatura (graus Celsius);

NO_2: Nitrito;

Cond: Condutividade elétrica;

OD: oxigênio dissolvido;

PH: potencial hidrogeniônico;

INPE: Instituto Nacional de Pesquisas Espaciais;

INMET: Instituto Nacional de Meteorologia;

RGB: Red, Blue e Green (Vermelho, Azul e Verde);

MMA: Ministério do Meio Ambiente;

ALT: Alanina aminotransferase;

AST: Aspartato aminotransferase;

CAT: Catalase;

SOD: Superóxido dismutase;

Kg: Quilograma;

mg/L: Miligrama por litro;

IMPACTOS DA COMPLEXIDADE AMBIENTAL E ALIMENTAÇÃO NOS ESTADOS AFETIVOS DE CARACÍDEOS PANTANEIROS

RESUMO

Em resposta à crescente preocupação com a qualidade de vida de peixes criados em sistemas de aquicultura, o presente estudo enfatiza a importância do enriquecimento ambiental como ferramenta estratégica para aprimorar o bem-estar animal. Este trabalho está subdividido em três capítulos. O primeiro uma revisão sistemática sobre enriquecimento ambiental utilizados em peixes e seus impactos na saúde e bem-estar e a possibilidade de aplicabilidade no sistema de produção e em aquários. O segundo capítulo aborda a plasticidade fisiológica e comportamental de espécimes de *Moenkhausia bonita* provenientes de áreas sujeitas a oscilações ambientais. O terceiro capítulo trata-se de estudo de comportamento correlacionados com as variáveis do perfil metabólico de *Moenkhausia bonita* submetidos a estresses. Os dados presentes na literatura apontam com consistência que o uso de enriquecimento ambiental pode ser um fator positivo para melhorar os estados cognitivos dos peixes que reflete nos aspectos relacionados a saúde e bem-estar resultando em longevidade. O capítulo que trata da adaptabilidade frente às mudanças ambientais evidenciou a elevada plasticidade da *Moenkhausia bonita*, destacando sua capacidade de ajustar respostas fisiológicas e comportamentais diante de variações ambientais que podem ou não ser decorrentes da atividade humana, cada vez mais presentes nos ecossistemas atuais.

Palavras-chaves: Enriquecimento, plasticidade, comportamento, metabolismo e viés cognitivo.

IMPACTS OF ENVIRONMENTAL COMPLEXITY AND FEEDING ON THE AFFECTIVE STATES OF PANTANAL CHARACIDS

ABSTRACT

The ornamental fish market has been experiencing consistent global growth, primarily driven by the unique phenotypic traits of these animals, which attract a wide range of consumers, from amateur collectors to industry professionals. Achieving prominence and relevance in this market directly depends on the conditions in which fish are kept, making it essential for suppliers to provide suitable environments that are rich in stimuli and free from idleness, thereby promoting both the physical and behavioral welfare of the animals. In response to the growing concern for the quality of life of fish raised in aquaculture systems, this study emphasizes the importance of environmental enrichment as a strategic tool to enhance animal welfare. The systematic review conducted followed pre-established criteria and clear methodological steps, demonstrating that environmental enrichment constitutes a key variable across different types of rearing and management systems. The second chapter addresses the physiological and behavioral plasticity of *Moenkhausia bonita* specimens from areas subject to constant environmental fluctuations, with samples collected in the Pantanal region during two distinct seasons. The results indicated significant changes in the animals' oxidative metabolism, suggesting a high adaptive capacity in response to environmental changes. These findings underscore the importance of environmental enrichment and the understanding of physiological plasticity for management practices that promote the health and welfare of ornamental fish in sustainable production systems.

Keywords: Enrichment, plasticity, behavior, metabolism, and cognitive bias.

CAPÍTULO 1 - CONSIDERAÇÕES INICIAIS

INTRODUÇÃO

O Pantanal é reconhecido por sua variedade excepcional e diversificada de espécies e se destaca como uma extensão de áreas úmidas, classificada entre as maiores do planeta (Silva et al. 2024). No entanto, o equilíbrio ecológico dessa região notável está exposto a diversos tipos de mudanças, incluindo alterações climáticas e interferência humana. (Caballero et al. 2025; Guerra et al. 2025). A fim de mitigar os efeitos adversos das alterações climáticas, esta iniciativa procura garantir a preservação a longo prazo dessa fauna inestimável. No Brasil, a despeito de sua elevada diversidade de peixes de água doce (Nogueira et al. 2010), é crescente a degradação e poluição difusa de seus rios (Caballero et al. 2025), especialmente aqueles de menor volume que abrigam espécies de pequeno porte (Batista et al. 2024).

O aumento da temperatura em decorrência do aquecimento global vem alterando a dinâmica de temperatura ao longo dos ciclos de verão e inverno (Naylor et al. 2021a). Os crescentes impactos sobre as espécies na natureza incluem mudanças na distribuição e na abundância (Islam et al. 2022; Caballero et al. 2025; Gu et al. 2025).

Os peixes de água doce constituem um dos grupos mais impactados pelas mudanças climáticas (Reid et al. 2013), principalmente porque eles dependem de temperaturas e chuvas bem definidas ao longo do ano para a manutenção de seus ritmos sazonais (Vazzoler 1996, Andrade et al. 2015; Portella et al. 2021). As ameaças que as mudanças climáticas impõem aos peixes de água doce são muito preocupantes do ponto de vista da conservação das espécies, especialmente se considerado que estes animais já são seriamente impactados pelas ações antrópicas (Abisha et al. 2022). Diante deste cenário, é fundamental o desenvolvimento de protocolos de conservação destas espécies em aquários, para preservação da espécie e possível repovoamento quando necessário (Marcacini de Araujo et al. 2024).

A aquicultura de peixes ornamentais é uma importante ferramenta para reduzir o impacto da retirada de espécies de organismos aquáticos do seu ambiente natural (Marcacini de Araujo et al. 2024), além de preservar os estoques e promover a conservação dessas espécies submetidas as mudanças proporcionadas pelas alterações ao meio ambiente sejam por poluição ou por adversidades climáticas (Sinha et al. 2023). Sendo assim, a aquicultura pode além de abastecer a aquariofilia gerando renda para o sistema de produção, promove conscientização ambiental e conservação dos peixes que podem entrar em risco de extinção (Jha and Gupta 2021). No entanto, um dos gargalos da produção aquícola e manutenção das espécies está associado ao manejo alimentar e manutenção do ambiente que promova saúde e bem-estar (Santos et al. 2024).

Destaca-se que a produção de espécies sensíveis às intempéries ambientais pode ser utilizada como ferramenta de ensino associado com sensibilização torna-se uma alternativa válida e imprescindível para diminuir os impactos ambientais (Ruggerio 2021). No entanto, ainda há lacunas do conhecimento nesta área, uma delas é como estes peixes se comportam na natureza e suas habilidades de lidar com a diversidade e sua preservação (Kumar et al. 2013; Naylor et al. 2021b) e sobrevivência em ambientes de aquário para que além da manutenção possam reproduzir e deixar descendentes viáveis (Marcacini de Araujo et al. 2024). Utilizar, portanto, o comportamento de organismos em condições controladas, pode fornecer informações indiretas, que possibilitam realizar inferências sobre a qualidade ambiental do ecossistema (Lima et al. 2014; Anderson et al. 2022).

Entender como os animais interagem emocionalmente com o ambiente em que estão inseridos e como manifestam essas emoções, tem se tornado importante devido a crescente preocupação com o bem-estar, principalmente daqueles criados sob cuidados humanos (Kremer et al. 2020a). Buscando compreender como as emoções se manifestam em seres não verbais, pode ser feita avaliação de forma indireta, como em testes de preconceito cognitivo (Kremer et al. 2020a; Anderson et al. 2021, 2022). Os estados afetivos que os animais apresentam podem influenciar na forma como tomam suas decisões (Anderson et al. 2021).

No entanto, há uma escassez de informações de peixes de água doce mantidos em sistemas de aquários públicos e coleções zoológicas. O atendimento dos requisitos básicos para manutenção de peixes em ambientes de cativeiro é fundamental para o sucesso da manutenção da vida. A combinação de fatores indicadores comportamentais, de desempenho e fisiológicos pode ser utilizada para avaliar o bem-estar e com base nestas informações promover modelos para análise destas espécies em ambientes naturais.

REVISÃO DE LITERATURA

Mudanças climáticas e aquicultura

A indústria de peixes ornamentais movimenta entre 15 e 30 bilhões de dólares anualmente. Além de sua relevância econômica, a aquariofilia é um dos principais hobbies do mundo, e os peixes estão entre os animais de estimação mais comercializados (Cardoso et al., 2021).

No Brasil, as exportações de peixes ornamentais alcançaram em 2018 cerca de 6,5 milhões de dólares, com destaque para São Paulo e Minas Gerais como principais polos produtores. A Zona da Mata mineira é a maior produtora nacional, tendo a China (Hong Kong) e Taiwan como principais importadores (Valenti et al., 2021; Cardoso et al., 2021). Entretanto, grande parte do interesse internacional ainda recai sobre espécies brasileiras oriundas do extrativismo.

Aquários e zoológicos desempenham papel importante tanto na manutenção da diversidade genética quanto na conservação de espécies ameaçadas, cuja população natural tem diminuído drasticamente em função de problemas ambientais, como aumento da temperatura e, no caso do Pantanal, a degradação da qualidade da água provocada por queimadas. O Pantanal, uma das maiores áreas úmidas do planeta, é um dos biomas mais afetados pelas mudanças climáticas, que colocam em risco seu equilíbrio ecológico (Guerra et al. 2025).

Apesar da elevada diversidade de peixes de água doce no Brasil, aproximadamente 2.500 espécies descritas (Nogueira et al. 2010), a degradação e a poluição difusa dos rios ameaçam sobretudo espécies de pequeno porte (Santos et al. 2022; Caballero et al. 2025). As mudanças climáticas intensificam essas pressões: há consenso científico de que o aquecimento global resulta, em grande parte, da atividade humana desde meados do século XX, com impactos como aumento de temperaturas extremas, alterações no regime de chuvas, secas severas e acidificação de corpos d'água (Reid et al. 2019a, Abisha et al. 2022).

Essas alterações têm consequências diretas para os peixes, por serem ectotérmicos, não possuem mecanismos fisiológicos de regulação da temperatura corporal (Daw et al. 2009; Abisha et al. 2022). O aquecimento global modifica ciclos sazonais, afeta reprodução, uso de habitat e interações tróficas (Neokye et al. 2024), além de relatos de diminuição do tamanho corporal e redistribuição de espécies sensíveis em comunidades de peixes neotropicais (Batista et al. 2024).

No entanto, o conhecimento disponível ainda é limitado, concentrando-se em espécies de regiões temperadas, como os salmonídeos do hemisfério norte (Pounder et al. 2016, Villarroel et al. 2021, Gesto and Jokumsen 2022, Brunet et al. 2022, Vasdravanidis et al. 2022, Eidsmo et al. 2023, Anderson et al. 2022, Villalba et al. 2024, Prentice et al. 2025), tilápias (*Oreochromis niloticus*) (Ariyomo et al. 2024)(Favero Neto and Giaquinto 2020, Yi et al. 2022, Tatemoto et al. 2021, Roy et al. 2021) e espécies de modelagem farmacêutica, como o zebrafish (*Danio rerio*) (De Pasquale et al. 2016, Giacomini et al. 2016, White et al. 2017, Barcellos et al. 2018, Marchetto et al. 2021, DePasquale et al. 2021, Marchetto et al. 2021, Sen Sarma et al. 2023, Jorge et al. 2023, Gazzano et al. 2025). Isso evidencia a necessidade de mais estudos voltados para peixes tropicais e subtropicais, especialmente frente à realidade dos ecossistemas sul-americanos (de Sousa et al. 2024; Siqueira et al. 2024).

A aquicultura ornamental surge como alternativa sustentável ao extrativismo, contribuindo para a conservação de espécies e para a conscientização ambiental (Jha and Gupta 2021; Sinha et al. 2023). Entretanto, ainda há desafios relacionados ao manejo alimentar e à manutenção de condições ambientais que assegurem saúde e bem-estar. O cultivo de espécies sensíveis pode também funcionar como ferramenta de ensino e sensibilização (Ruggerio 2021), além de fornecer subsídios para inferir sobre a qualidade ambiental em cenários de estresse térmico (Islam et al. 2022).

As mudanças climáticas representam, portanto, um desafio para a aquicultura, mas também uma oportunidade de inovação (Abisha et al. 2022; Vasdravanidis et al. 2022). A adoção de sistemas resilientes e climaticamente inteligentes pode sustentar benefícios ecológicos, sociais e econômicos, reduzindo vulnerabilidades e promovendo sustentabilidade (Valenti et al. 2021; Abisha et al. 2022). Preservar a biodiversidade e adaptar os sistemas produtivos será essencial para que a aquicultura continue sendo uma ferramenta estratégica de conservação e desenvolvimento em um cenário de aquecimento global.

COMPORTAMENTO DE PEIXES

O estudo do comportamento de peixes tem ganhado destaque nas últimas décadas, principalmente devido à crescente preocupação com o bem-estar animal em sistemas de produção e em ambientes controlados (Kremer *et al*. 2020a). Entender como esses organismos interagem emocionalmente com o ambiente e como expressam tais estados é essencial para o manejo adequado, pois alterações comportamentais refletem diretamente nas condições de saúde, desempenho e sobrevivência (Arechavala-Lopez *et al*. 2020).

Como os peixes são animais não verbais, a avaliação de seus estados afetivos ocorre de forma indireta, por meio de parâmetros observáveis (Tincy V. *et al*. 2021). Uma das ferramentas recentes é o teste de viés cognitivo, que permite inferir o estado emocional dos animais com base em suas escolhas em situações de incerteza (Anderson *et al*. 2021, Anderson *et al.* 2022) . Assim, compreende-se que estados emocionais influenciam o processo de tomada de decisão, podendo resultar em maior cautela, exploração ou evasão diante de determinados estímulos (Kremer et al. 2020b).

Na aquicultura ornamental, no entanto, ainda há escassez de informações comportamentais específicas, o que dificulta a criação de protocolos de bem-estar (Stevens *et al*. 2017). A manutenção de peixes em sistemas produtivos exige o atendimento a requisitos básicos, como qualidade da água, densidade de estocagem, manejo alimentar e enriquecimento ambiental (Bjelland et al. 2025). O não cumprimento desses requisitos leva a alterações comportamentais, como aumento de agressividade, canibalismo, letargia, perda de apetite e diminuição da reprodução (Maia et al. 2025).

Indicadores comportamentais podem ser utilizados em conjunto com marcadores fisiológicos (cortisol plasmático, frequência respiratória, taxa de ventilação branquial, alterações metabólicas) e parâmetros de desempenho (crescimento, sobrevivência, reprodução) para a avaliação do bem-estar. Esse tripé de comportamento, fisiologia e desempenho, fornecem subsídios robustos para interpretar o estado geral dos animais e elaborar estratégias de manejo (Maia et al. 2025).

Entre os comportamentos mais estudados em peixes, destacam-se:

- **Exploração e uso do espaço**: peixes saudáveis exploram o ambiente, enquanto indivíduos estressados tendem ao isolamento ou ao comportamento de fundo.
- **Interações sociais**: incluem hierarquia, agressividade, formação de cardumes e comportamento de dominância.
- **Alimentação**: a forma e a rapidez com que o peixe se alimenta refletem sua motivação e adaptação ao ambiente.
- **Comportamento reprodutivo**: corte, escolha de parceiros, construção de ninhos e cuidado parental são fortemente afetados pela qualidade ambiental.
- **Respostas a estímulos externos**: movimentação abrupta, fuga, aumento da ventilação ou imobilidade podem indicar estresse.

Modelos de avaliação comportamental (Tab.1), quando integrados a condições ambientais e parâmetros fisiológicos, podem ser aplicados tanto em sistemas de produção quanto em ambientes naturais, auxiliando na criação de protocolos de bem-estar e conservação. Além disso, a implementação de enriquecimento ambiental, usando como exemplo o uso de estruturas, variação de iluminação, enriquecimento alimentar e heterogeneidade espacial (Brunet et al. 2022) tem se mostrado eficaz na promoção de comportamentos naturais e na redução de estresse em peixes ornamentais.

Dessa forma, o estudo do comportamento de peixes não apenas contribui para avanços na aquicultura ornamental**,** mas também auxilia na conservação de espécies, no desenvolvimento de práticas de manejo sustentáveis e no fortalecimento do debate sobre bem-estar em organismos aquáticos.

Tabela 1: Relação entre a descrição e a interpretação de comportamentos exibidos por peixes.

Comportamento	Descrição	Interpretação / Significado	Relação com bem-estar
Formação de cardume	Natação em grupo coesa, com movimentos sincronizados	Estratégia de proteção, socialização	Indica segurança e adaptação ambiental
Isolamento / segregação	Permanência afastada do grupo ou em áreas de fundo	Estresse, doença ou submissão	Sinal de alerta para problemas ambientais ou sanitários
Agressividade / ataques	Mordidas, perseguições, disputas por território	Competição por recursos, densidade elevada	Bem-estar comprometido; risco de ferimentos
Natação errática	Movimentos rápidos, descoordenados, batidas contra o vidro ou superfície	Estímulos estressores (ruído, manejo, má qualidade da água)	Indicador claro de estresse agudo
Lentidão / letargia	Redução na movimentação, permanência no fundo	Estresse crônico, hipóxia, doenças	Bem-estar comprometido; necessidade de intervenção
Atividade exploratória	Investigação ativa do ambiente, interação com objetos	Curiosidade e adaptação	Indica boa condição de bem-estar
Alimentação normal	Resposta imediata ao alimento, ingestão ativa	Estado fisiológico saudável	Indica conforto e ausência de estresse
Recusa alimentar	Ignora ou rejeita o alimento	Estresse, doença, má qualidade da água ou baixa palatabilidade	Alerta crítico para saúde ou ambiente
Comportamento reprodutivo	Corte, construção de ninhos, desova, cuidado parental	Condição ambiental e fisiológica adequada	Bem-estar preservado
Aumento da ventilação branquial	Batimentos operculares rápidos, respiração ofegante	Baixo oxigênio, temperatura elevada, acúmulo de amônia	Indicador de estresse fisiológico

Pigmentação alterada	Escurecimento ou palidez súbita	Resposta a estresse, dominância ou submissão	Sinal de alteração fisiológica

Enriquecimento ambiental

A complexidade ambiental exerce impacto direto no funcionamento biológico e no comportamento dos animais, influenciando aspectos relacionados ao bem-estar (Arechavala-Lopez et al. 2020). Em peixes, diversos estudos demonstram que o enriquecimento ambiental pode promover melhorias fisiológicas e comportamentais (Anderson et al. 2021, 2022; Roy et al. 2021; Marcacini de Araujo et al. 2024).

O enriquecimento ambiental é um princípio de bem-estar animal voltado para a melhoria da qualidade de vida em cativeiro, fornecendo estímulos que favoreçam condições psicológicas e fisiológicas adequadas (Granzotti et al. 2018). Esse enriquecimento pode ser classificado em ativo (quando exige interação direta dos animais, como manipulação de objetos ou desafios alimentares) ou passivo (quando envolve modificações ambientais sem necessidade de ação imediata, como alteração de cores ou iluminação).

Dada a grande diversidade de espécies mantidas em sistemas de produção e exibições públicas, é necessário adotar uma abordagem específica, considerando características fisiológicas, ecológicas e comportamentais de cada grupo (Marcacini de Araujo et al. 2024)

Exemplos de enriquecimento ambiental em peixes:

- **Enriquecimento físico/estrutural**: inclusão de substratos, abrigos, barreiras visuais, variação do fluxo de água, alteração periódica da coloração de fundo, fotoperíodo e intensidade luminosa.
- **Enriquecimento alimentar**: diversificação de dietas, variação nos horários e locais de fornecimento, utilização de comedouros diferenciados ou desafios alimentares que estimulem habilidades naturais de captura ou forrageamento.
- **Enriquecimento social**: manutenção de cardumes com número adequado de indivíduos, como em espécies naturalmente gregárias, garantindo a expressão de comportamentos coletivos típicos.
- **Enriquecimento cognitivo/treinamento**: atividades de condicionamento, como alimentação direcionada ou tarefas simples, que podem reduzir estresse, facilitar manejo e estimular processos de aprendizagem.

Entretanto, nem todo enriquecimento resulta em experiências positivas (Granzotti et al. 2018). A implementação inadequada pode gerar efeitos adversos, como aumento da agressividade em populações com poucos abrigos disponíveis, levando à competição e hierarquização indesejada (Näslund and Johnsson 2016). Dessa forma, todo enriquecimento deve ser monitorado, avaliado e ajustado, garantindo que promova de fato melhorias no bem-estar individual e coletivo (Garcia et al.).

IMPORTÂNCIA DO ESTUDO DE METABOLISMO EM PEIXES E SUA CONEXÃO COM O COMPORTAMENTO

No ambiente de cultivo, durante o processo de produção, os peixes estão sujeitos a diversas situações que podem alterar o metabolismo, desencadeando respostas fisiológicas e comportamentais que afetam a produtividade, a sobrevivência, a saúde e o bem-estar (Diniz and Honorato 2012). Para acompanhar essas respostas, avaliações fisiológicas específicas, como a análise do metabolismo hepático e do metabolismo oxidativo**,** são amplamente utilizadas, pois refletem alterações precoces na saúde em resposta a agentes estressores (Ota et al. 2019; Fabrizzi et al. 2025). Essas informações permitem inferir como os peixes lidam com as condições impostas pelo ambiente de cultivo (Reges et al. 2024).

O estresse é um dos principais fatores moduladores do metabolismo (Siqueira et al. 2024). Ele pode alterar a homeostase e induzir respostas fisiológicas e comportamentais (Honorato et al. 2024) caracterizadas pela elevação de hormônios como o cortisol e as catecolaminas**,** que auxiliam na superação de situações adversas (Dong et al. 2023). Porém, sob condições crônicas, esses mecanismos tornam-se insuficientes, comprometendo a adaptação dos animais (Scardua et al. 2024)

Situações estressantes prolongadas podem reduzir o crescimento, suprimir o sistema imune, aumentar a suscetibilidade a doenças, afetar a pigmentação e até levar à mortalidade (Diniz and Honorato 2012). Nesse contexto, intervenções nutricionais, como o uso de aditivos funcionais, têm sido estratégias eficazes para mitigar os efeitos negativos e fortalecer os animais (do Couto et al. 2022; Siqueira et al. 2024; Dorce et al. 2025)

As alterações metabólicas se refletem diretamente no comportamento dos peixes (Tincy . et al. 2021; Marcacini de Araujo et al. 2024) Por exemplo, estados de estresse oxidativo e desequilíbrio hepático podem induzir comportamentos como natação errática, letargia, recusa alimentar ou agressividade (Siqueira et al. 2019), que funcionam como indicadores comportamentais de distúrbios fisiológicos (Siqueira et al. 2024; Dorce et al. 2025). Assim, a integração entre análises bioquímicas e observação comportamental oferece uma abordagem mais abrangente para compreender o bem-estar dos peixes em sistemas de cultivo, permitindo intervenções mais eficazes (Reges et al. 2024).

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OBJETIVOS

3.1 Objetivo Geral

Avaliar e descrever o efeito do enriquecimento ambiental e da alimentação com nutracêuticos sobre os estados afetivos e metabólicos de caracídeos pantaneiros.

3.2 Objetivos Específicos

Capítulo 2: Enriquecimento ambiental como mitigador de intemperes do sistema produtivo de peixes de água doce.

- Descrever a utilização de enriquecimento ambiental e seus efeitos no comportamento e aplicabilidade

Capítulo 3: Impacto do aquecimento global e da sazonalidade hídrica sobre as respostas morfofisiológicas de *Moenkhausia bonita* no Pantanal.

- Avaliar os efeitos de diferentes variações ambientais sobre os marcadores de estresse oxidativo em pequenos caracídeos pantaneiros.

Capítulo 2:

Capítulo elaborado na forma de artigo científico, submetido à revista *Environmental Biology* e estruturado de acordo com as normas da referida revista.

Environmental modulation of stress, behavior, and welfare in captive freshwater fish: a systematic review

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Abstract

Modern aquaculture increasingly seeks to balance production efficiency with sustainability, raising growing concern about fish welfare, since indicators of discomfort are often subtle and difficult to detect. In intensive culture systems, high stocking densities and environmental simplification may impair physiological resilience, behavior, and health, making environmental enrichment a relevant management strategy. This systematic review aimed to evaluate the effects of environmental enrichment on stress and welfare-related indicators in captive freshwater fish. Peer-reviewed studies published over the last ten years were selected using predefined search, screening, and eligibility criteria. The analyzed studies consistently showed that enriched environments are associated with reduced behavioral and physiological stress responses and greater expression of species-typical behaviors. However, a significant research gap remains regarding native and neotropical species, as most studies focus on model organisms or non-native taxa. Overall, the evidence indicates that environmental enrichment is an effective

tool to mitigate stress in captive freshwater fish, although further research is needed to expand its application across species and production contexts.

Keywords: Aquaculture management. Behavioral plasticity. Captive systems. Environmental complexity. Fish welfare indicators. Husbandry practices.

Introduction

The intensification of fish production systems has increased the need to understand how artificial environments influence behavior, physiology, and welfare in captive animals. Fish often exhibit stress responses through subtle behavioral, endocrine, and metabolic changes, which makes welfare assessment particularly challenging (Ashley 2007; Huntingford et al. 2006). Under these conditions, the culture environment becomes a central factor modulating the interaction between organisms and confinement-related stressors.

In aquaculture systems, major stressors include water quality fluctuations (Freire and Nicol 2024), high stocking densities (Sen Sarma et al. 2023; Anderson et al. 2022), limited environmental stimulation (Barcellos et al. 2018; Villarroel et al. 2021; Marchetto et al. 2021; Buenhombre et al. 2023), and spatial restriction (Vanderzwalmen et al. 2020; Honorato et al. 2024). These conditions can negatively affect growth, immune function, and survival, particularly in ornamental species (Ashley 2007; Huntingford et al. 2006). Conversely, the inclusion of physical structures, substrate variation, light modulation, and other habitat-mimicking elements can increase environmental complexity and promote improved welfare outcomes (Näslund and Johnsson 2016; Buenhombre et al. 2023).

Environmental enrichment has emerged as a promising strategy to mitigate these stressors by increasing habitat complexity and promoting behavioral and physiological responses closer to those observed under natural conditions (Zhang et al. 2020). Enrichment approaches are commonly classified as structural, sensory, social, and occupational, involving physical objects, visual or auditory stimuli, social interaction opportunities, and cognitive challenges (De Pasquale et al. 2016; Pereira et al. 2020; Kleiber et al. 2023). These interventions have been associated with reduced aggression, modulation of endocrine stress responses, and increased behavioral plasticity in freshwater fish.

Freshwater ornamental fish production represents a relevant and expanding sector of global aquaculture, both economically and in terms of species diversity (Biondo et al. 2024; Costa et al. 2024). However, production intensification combined with physical system constraints often imposes challenging environmental conditions that may compromise performance, health, and welfare (Baciadonna and McElligott 2015). In this context, synthesizing current evidence on enrichment strategies is essential. Therefore, this systematic review aimed to compile and critically analyze the scientific literature on environmental enrichment in captive freshwater fish, focusing on its effects on stress, behavior, and welfare indicators, and to identify knowledge gaps and future research directions for application in culture systems.

Materials and Methods

This study was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The PRISMA framework was adopted to ensure transparency, reproducibility, and methodological rigor in the literature search, screening, eligibility assessment, and data synthesis procedures (Fig. 1). The review protocol was not prospectively registered, given the exploratory scope of the study and the limited volume of specialized literature specifically addressing environmental enrichment in freshwater fish.

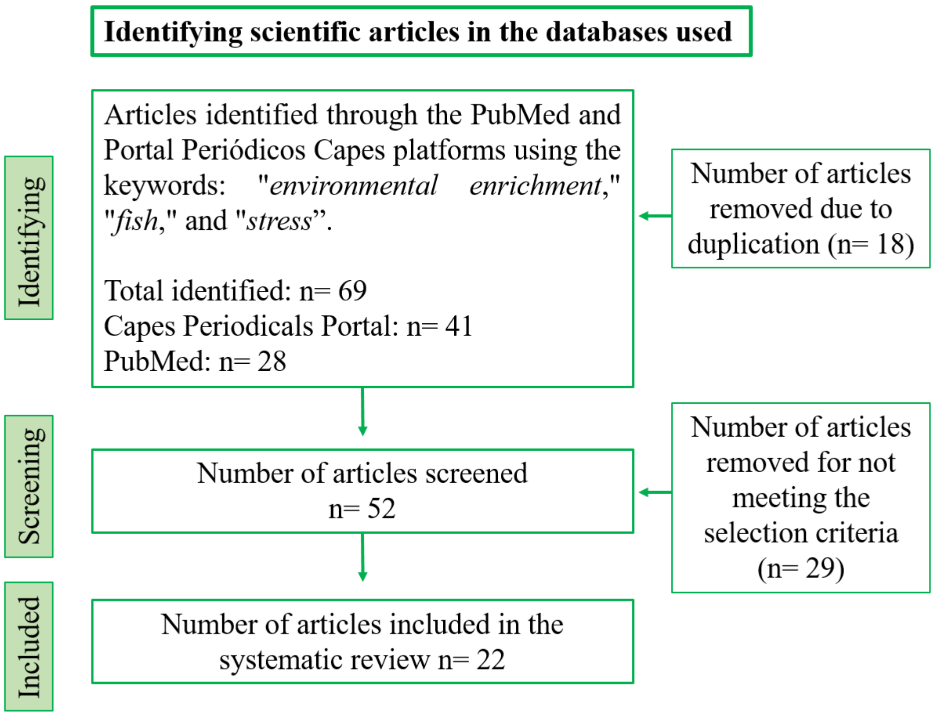

Fig. 1 PRISMA flowchart of the process for identifying, screening, and including studies selected for the systematic review on environmental enrichment in freshwater fish. Source: Adapted from Brazil (2012); own elaboration (2025)

The review question was defined using the PICO framework (Population, Intervention, Comparison, Outcome). The population of interest comprised freshwater fish maintained in captivity. The intervention corresponded to environmental enrichment strategies. The comparison condition included non-enriched or structurally simplified environments. Outcomes of interest included behavioral and physiological indicators associated with stress and welfare.

Accordingly, the guiding question of this review was: What are the effects of environmental enrichment, compared with non-enriched environments, on behavioral and physiological stress-related responses in captive freshwater fish?

The literature search was conducted between May and June 2025 using PubMed and the CAPES Journal Portal, a Brazilian academic database gateway that provides full-text access to major international indexing platforms, including Web of Science, Scopus, ScienceDirect, and SpringerLink. This combined approach was used to ensure broad coverage of relevant peer-reviewed literature.

The search string applied in both platforms was: "environmental enrichment" AND "fish" AND "stress". Only studies published between 2016 and 2025 were considered. Searches were restricted to peer-reviewed journal articles. No automatic filters regarding study design were applied at the search stage in order to maximize sensitivity. The literature search and initial screening were conducted by a single reviewer. To reduce selection bias, predefined eligibility criteria were strictly applied throughout all screening stages.

Studies were included when they met the following criteria:
- involved freshwater fish Species;
- evaluated environmental enrichment interventions;
- assessed behavioral and/or physiological indicators related to stress or welfare;
- were original peer-reviewed research articles;
- were published within the defined ten-year time window.

Studies were excluded when they:
- were reviews, abstracts, theses, or dissertations;
- involved non-fish organisms;
- focused exclusively on marine fish;
- did not include an enrichment intervention;
- did not report stress- or welfare-related outcomes;
- Screening and selection process.

All retrieved records were compiled and duplicate entries were removed prior to screening. Titles and abstracts were then screened against the eligibility criteria. Records that did not meet inclusion criteria were excluded at this stage. Full texts of potentially eligible articles were subsequently assessed for final inclusion. Reasons for exclusion at the full-text stage were documented. The complete identification, screening, eligibility, and inclusion workflow is presented in the PRISMA flow diagram (Fig. 1).

Data extraction from the included studies was performed using a structured approach. The following variables were prioritized:
- fish species studied;
- type of environmental enrichment applied;
- enrichment category (e.g., structural, sensory, social, cognitive, occupational);
- stress and welfare indicators measured;
- main behavioral and physiological outcomes;
- general direction of observed effects.

Given the heterogeneity of species, enrichment protocols, and outcome measures, a quantitative meta-analysis was not considered appropriate. Therefore, results were synthesized using a qualitative narrative approach focused on identifying methodological trends, recurring outcome patterns, and knowledge gaps in the field of environmental enrichment in freshwater fish.

Results

The systematic search initially identified 69 scientific articles. After removal of duplicate records (n = 18), 52 studies remained for title and abstract screening. Of these, 29 were excluded for not meeting the eligibility criteria. Following full-text assessment, 22 articles were included in the final qualitative synthesis, as detailed in the PRISMA flow diagram (Fig. 1).

The included studies were published between 2015 and 2025, indicating a progressive increase in scientific interest in environmental enrichment and fish welfare over the past decade. Publication frequency rose notably after 2020, with a peak in 2023 (Fig. 2), suggesting recent consolidation of this topic within experimental and applied fish research.

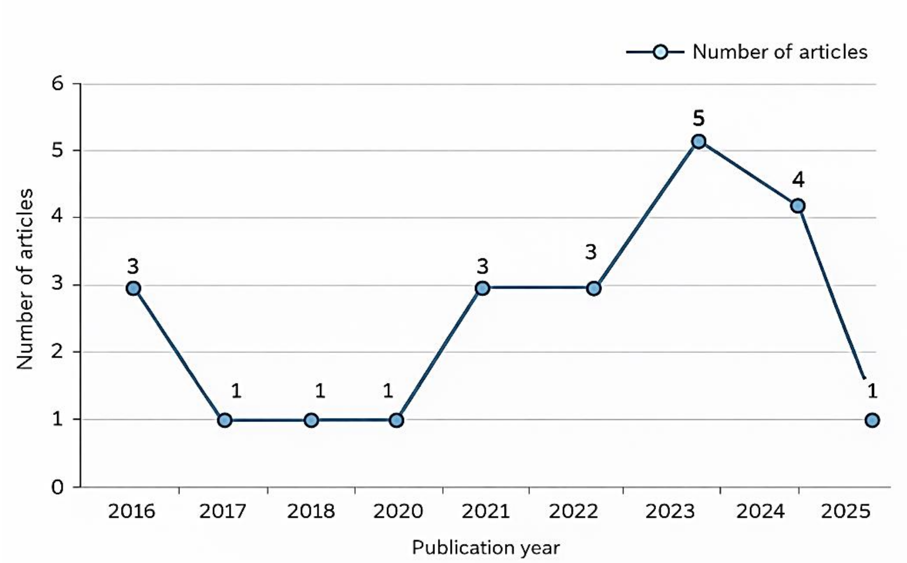

Fig. 2 Temporal distribution of the number of scientific articles published between 2016 and 2025 and included in the systematic review on environmental enrichment in freshwater fish. Source: Author's own elaboration (2025)

The freshwater fish species investigated were predominantly teleosts, with a strong concentration in model organisms. Zebrafish (*Danio rerio*) was the most frequently studied species across the selected articles. Other species included rainbow trout (*Oncorhynchus mykiss*), Nile tilapia (*Oreochromis niloticus*), sterlet (*Acipenser ruthenus*), yellowtail lambari (*Astyanax bimaculatus*), African catfish (*Clarias gariepinus*), and platy (*Xiphophorus variatus*) (Fig. 3). Overall, model and laboratory-adapted species were markedly overrepresented, whereas native and neotropical freshwater species were comparatively underrepresented in enrichment-based welfare studies.

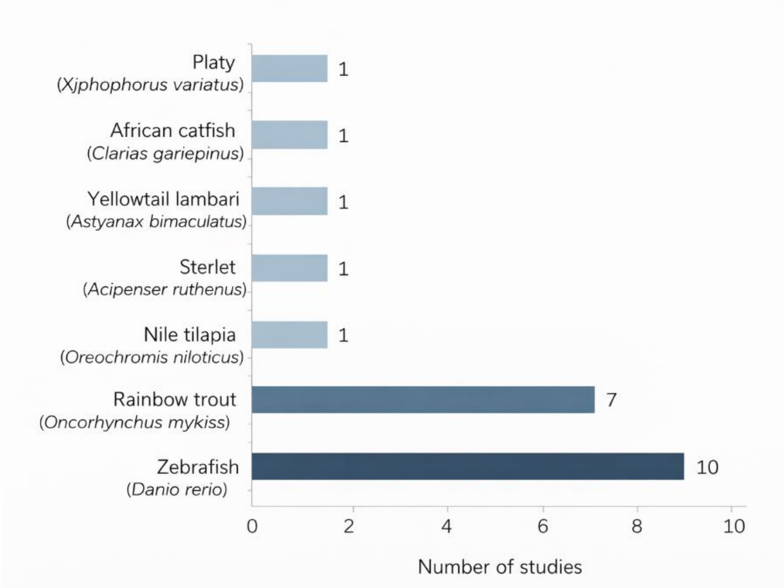

Fig. 3 Distribution of freshwater fish species investigated in the studies included in the systematic review, indicating the number of studies associated with each species. Source: Author's own elaboration (2025)

Structural enrichment was the most commonly applied enrichment modality, reported in 14 of the 22 included studies (Table 1). Structural approaches primarily involved the addition of physical elements such as natural or artificial plants, substrate materials, shelters, and PVC tubes designed to increase habitat complexity and provide refuge opportunities.

Other enrichment modalities were less frequently represented. Auditory enrichment was evaluated in two studies, cognitive enrichment in one study, active (exercise-based) enrichment in two studies, and social enrichment in two studies. One study combined enrichment protocols with pharmacological interventions. This distribution indicates a strong methodological preference for structural modifications compared with sensory, cognitive, or social approaches.

Tab. 1 Classification of the types of environmental enrichment used in the studies included in the systematic review on freshwater fish, indicating the number of articles and their respective authors by category

TYPE	NUMBER OF ARTICLES	AUTHORS

Structural Enrichment	14	Vanderzwalmen et al. (2020), Pounder et al. (2016), Gazzano et al. (2025), Fazekas et al. (2023), Brunet et al. (2022), Ariyomo et al. (2024), Gesto and Jokumsen (2022), Jorge et al. (2023), De Pasquale et al. (2016), Eidsmo et al. (2023), Byrd et al. (2024), De Sousa et al. (2024), Ojelade et al. (2022) and De Pasquale et al. (2021).
Auditory Enrichment	2	Barcellos (2018) and Marchettoa et al. (2024)
Cognitive Enrichment	1	Kleiber et al. (2024)
Active Enrichment	2	Villarroel et al. (2021) and Villalba (2023)
Social Enrichment	2	White et al. (2017) and Sarma et al. (2023)
Enrichment and addition of drugs	1	Cristina et al. (2016)

Across the analyzed period, enrichment research showed a gradual expansion in both methodological diversity and species coverage. Earlier studies were more frequently based on structural modifications and model species, whereas more recent work has begun to explore cognitive, sensory, and occupational enrichment strategies across a broader range of taxa (Fig. 4). Nevertheless, zebrafish remains the dominant experimental model throughout the timeline.

The included studies assessed stress and welfare outcomes using a combination of behavioral and physiological indicators. Behavioral endpoints commonly included activity patterns, exploratory behavior, aggression levels, anxiety-like responses, and social interactions. Physiological indicators most frequently involved cortisol measurements, either through tissue sampling or non-invasive waterborne hormone quantification.

Across studies, enriched environments were consistently associated with reduced stress-related behavioral responses, lower anxiety-like behavior, and improved expression of species-typical behavioral repertoires. Several studies also reported physiological benefits, including reduced cortisol levels, improved survival, and enhanced reproductive or growth-related parameters in enriched conditions.

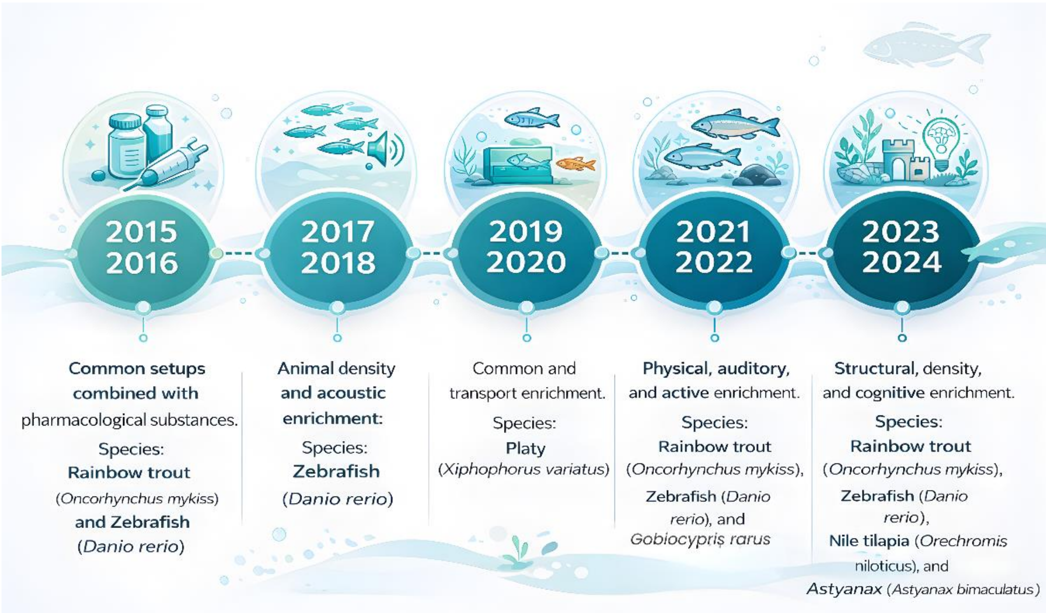

Fig. 2 Timeline representing the main milestones in the literature on environmental enrichment in fish. Source**:** Created by the authors with AI-assisted graphic generation (2025)

Keyword frequency analysis of the included studies (Fig. 5) indicated strong thematic clustering around welfare, stress physiology, behavior, and environmental complexity. Terms related to enrichment, behavioral responses, and stress mitigation were dominant, reinforcing the conceptual linkage between habitat complexity and welfare-oriented outcomes in captive freshwater fish research.

Fig. 3 Word cloud generated from the keywords of the articles included in this review, highlighting the most frequent and relevant terms for the topic addressed. Source: Author's own elaboration (2025)

Discussion

Modern aquaculture, in its pursuit of efficiency and sustainability (FAO 2021; Valenti et al. 2021), faces the challenge of ensuring the welfare of animals that often exhibit subtle and not readily visible signs of discomfort (Siqueira et al. 2024; Dorce et al. 2025). Intensive production systems, typically characterized by high stocking densities (Santos et al. 2024) and simplified environments (Nogueira et al. 2010), may compromise animal welfare, making the development of innovative management strategies, such as environmental enrichment, increasingly necessary (Anderson et al. 2022).

In aquaculture, environmental enrichment can be implemented through different modalities, commonly classified as physical or structural, sensory, social, and occupational enrichment (Abreu et al. 2019; Pereira et al. 2020; Kleiber et al. 2023). Structural enrichment aims to simulate natural habitat complexity by providing shelters and substrates (Buenhombre et al. 2023; Ariyomo et al. 2024). Social enrichment can be used to optimize interactions among individuals (Espigares et al. 2022), whereas sensory and occupational enrichment strategies seek to stimulate perception and natural behavioral expression (Barcellos et al. 2018; Marchetto et al. 2021; Brunet et al. 2022).

Despite the commercial relevance of aquaculture, environmental enrichment has been more extensively investigated in model species (Brinn et al. 2012), particularly zebrafish (*Danio rerio*) (De Pasquale et al. 2016; Näslund and Johnsson 2016; White et al. 2017; DePasquale et al. 2021; Marchetto et al. 2021; Espigares et al. 2022; Buenhombre et al. 2023; Sen Sarma et al. 2023; Jorge et al. 2023; Byrd et al. 2024; Gazzano et al. 2025). Its widespread use in pharmacological and biomedical research, supported by genetic and physiological similarities with other vertebrates, has accelerated protocol development and understanding of enrichment effects (Giacomini et al. 2016; Jorge et al. 2023; Byrd et al. 2024).

Although these studies are not always directly transferable to large-scale production systems, they provide an important theoretical and methodological foundation for testing enrichment strategies in commercially relevant species such as Nile tilapia (*Oreochromis niloticus*) (Tatemoto et al. 2021; Yi et al. 2022; Ariyomo et al. 2024) and rainbow trout (*Oncorhynchus mykiss*) (Ashley 2007; Näslund and Johnsson 2016; Pounder et al. 2016; Rogers et al. 2020; Villarroel et al. 2021; Villalba et al. 2024; Mittún et al. 2025).

Despite the documented benefits, the adoption of environmental enrichment still faces resistance, particularly in research settings (Anderson et al. 2021). Experimental standardization is often prioritized to minimize variability, and the inclusion of structures such as stones or shelters may be considered a confounding factor (Marchetto et al. 2021; Jorge et al. 2023; Gazzano et al. 2025). However, this concern highlights the need to integrate welfare-oriented protocols into experimental design rather than treating them as external variables, thereby promoting physiological states that are more representative of the animals' biological condition (Reges et al. 2024).

The findings of the present review reinforce that environmental enrichment, across its different modalities, is an effective strategy for reducing stress and improving welfare indicators in captive fish. Structural enrichment emerged as the most frequently tested approach, with the use of plants, PVC tubes, and other substrates contributing to increased environmental complexity and stimulation. Such complexity supports the expression of natural behaviors, including foraging and shelter use (Pounder et al. 2016; Gazzano et al. 2025). In addition to behavioral benefits, physiological improvements have also been reported, including enhanced reproductive parameters and survival in *Astyanax bimaculatus* (De Sousa et al. 2024). Evidence from multiple studies confirms the applicability of structural enrichment in mitigating stress in culture systems (Vanderzwalmen et al. 2020; Gazzano et al. 2025; Fazekas et al. 2023).

Other enrichment modalities also showed relevant positive effects. Auditory enrichment, for example, reduced cortisol levels and anxiety-like behavior in socially isolated fish (Barcellos et al. 2018; Marchetto et al. 2021). Visual enrichment through the strategic placement of structural elements near tanks also contributed to cortisol reduction, indicating that environmental perception plays a role in physiological stress responses (Byrd et al. 2024).

Active enrichment strategies, which promote sustained swimming activity through induced water currents, were particularly promising for more active species such as rainbow trout (*Oncorhynchus mykiss*) (Mittún et al. 2025). By replicating flow conditions closer to natural habitats, these approaches can improve both welfare and performance (Villarroel et al. 2021; Villalba et al. 2024). Regarding assessment methods, the reviewed studies showed convergence in the combined use of behavioral and biochemical indicators. Swimming patterns and activity metrics provided behavioral insight (Vanderzwalmen et al. 2020), while cortisol remained the most widely used physiological marker (White et al. 2017; Byrd et al. 2024). The increasing use of non-invasive cortisol measurements in water represents an important methodological refinement that minimizes sampling-induced stress.

This review confirms that environmental enrichment is a powerful strategy for mitigating stress and promoting welfare in captive fish, but important research gaps remain.

The strong concentration of studies in model and ornamental species limits extrapolation to commercially important taxa. In addition, integration between physiological indicators, reproductive performance, and economic outcomes remains insufficiently explored. Expanding research toward native and economically relevant species, using more integrative welfare assessment frameworks, will be essential to strengthen the applicability of enrichment strategies in production systems.

It is important to recognize that promoting animal welfare in aquaculture is not limited to an ethical or productivity issue, but aligns with the Sustainable Development Goals (SDGs). Improving farming conditions and welfare contributes to goals such as food security (SDG 2), health (SDG 3), responsible production and consumption (SDG 12), and the conservation of aquatic life (SDG 14), positioning welfare as a strategic pillar for the sustainability of aquaculture (Lynch et al., 2020).

The relevance of these findings is further amplified under projected climate change scenarios. Ongoing environmental alterations, particularly rising temperatures and changing hydrological regimes, directly affect freshwater fish physiology, behavior, and distribution. Recent studies show that global warming alters thermal habitat profiles and exposes ectothermic fish to suboptimal temperatures, affecting metabolism, growth, and stress resistance (Agarwal et al. 2024; Nawaz and Mahmood 2024). Climate change has also been linked to increased disease risk and immune impacts in fish (Franke et al. 2024). Since environmental enrichment promotes stress mitigation and behavioral plasticity, these strategies may become increasingly important under climate-driven environmental instability. Enriched systems may therefore contribute not only to welfare under controlled conditions but also to improved behavioral and physiological resilience under ecological stress.

Conclusion

In conclusion, this systematic review reinforces the effectiveness of environmental enrichment in mitigating stress in captive fish, promoting the expression of natural behaviors and generating measurable physiological benefits. Structural enrichment stands out as the most extensively studied and consistently supported approach, although other modalities, including auditory, visual, and active enrichment, also demonstrate substantial potential.

For environmental enrichment to reach its full potential in aquaculture systems, additional studies are needed to evaluate its feasibility at larger production scales and across commercially important and native species. The consolidation of these practices can contribute not only to reduced production losses but also to improved ethical standards in animal management, strengthening the foundations of sustainable aquaculture.

The standardization of welfare assessment methods and the expansion of taxonomic coverage in enrichment research represent essential steps for translating scientific knowledge into applied production practices. Understanding environmental enrichment as a practical tool to modulate stress-related phenotypes in freshwater fish is therefore a key component of biologically informed captive management.

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Conceptualization: Leticia M. A. Conceição, Claucia A. Honorato da Silva.
Study design: Leticia M. A. Conceição.
Literature search and screening: Leticia M. A. Conceição.
Data curation: Leticia M. A. Conceição.
Methodology: Leticia M. A. Conceição.
Data analysis and visualization: Leticia M. A. Conceição.
Writing — original draft: Leticia M. A. Conceição.
Writing — review and editing: Liliane S. Matos, Claucia A. Honorato da Silva
All authors read and approved the final manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Ethics Approval

This study is a systematic review based exclusively on previously published data and did not involve experimental procedures with animals or human participants. Therefore, ethics committee approval was not required.

Data Availability

All data analyzed in this study are derived from published articles and are available in the cited references. Extracted datasets generated during the review process are available from the corresponding author upon reasonable request.

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Capitulo 3:

Capítulo elaborado na forma de artigo científico, submetido à revista *Neotropical Ichthyology* e estruturado de acordo com as normas da referida revista.

Title:

Impact of Global Warming and Water Seasonality on the Morphophysiological Responses of *Moenkhausia bonita* (Characiformes: Characidae) in the Pantanal

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Abstract: Free-living species constantly face environmental challenges, and anthropogenic changes intensify the need for adaptive physiological and behavioral responses to ensure survival. This study aimed to understand how fish respond physiologically to distinct environmental challenges, including increased temperature, sediment deposition, and changes in water quality. Sampling was conducted in November 2023 (summer) and July 2024 (winter). Measurements of total length, standard length, and head size were recorded to compare individual growth patterns between seasons. Analyses of hepatic metabolism were conducted to assess the activity of enzymes related to oxidative stress, and fish coloration was measured to investigate possible seasonal variations. Principal Component Analysis (PCA) revealed a clear separation between seasonal groups, highlighting the correlation between color parameters and oxidative metabolism enzymes. The results showed that fish collected in summer exhibited more intense coloration and lower activity of oxidative metabolism enzymes, while winter individuals displayed paler coloration and increased enzyme activity associated with stress. These findings suggest that seasonal variations induce physiological and metabolic adjustments, reflecting a redistribution of energy reserves according to environmental conditions. Such responses indicate the adaptive plasticity of the species in the face of environmental fluctuations characteristic of the Pantanal.

Keywords: Physiological plasticity, Environmental changes, Seasonal variations, Metabolic enzymes, Body coloration.

Resumo: Espécies de vida livre enfrentam constantemente desafios ambientais, e as mudanças antrópicas intensificam a necessidade de respostas fisiológicas e comportamentais adaptativas para garantir a sobrevivência. Este estudo teve como objetivo compreender como os peixes respondem fisiologicamente a distintos desafios ambientais, incluindo o aumento da temperatura, a deposição de sedimentos e alterações na qualidade da água. As coletas foram realizadas em novembro de 2023 (verão) e julho de 2024 (inverno). Medidas de comprimento total, comprimento padrão e tamanho da cabeça foram registradas para comparar os padrões de crescimento individual entre as estações. Análises do metabolismo hepático foram conduzidas para avaliar a atividade de enzimas relacionadas ao estresse oxidativo, e a coloração dos peixes foi mensurada para investigar possíveis variações sazonais. A Análise de Componentes Principais (PCA) revelou uma clara separação entre os grupos sazonais, destacando a correlação entre parâmetros de cor e enzimas do metabolismo oxidativo. Os resultados mostraram que os peixes coletados no verão exibiram coloração mais intensa e menor atividade das enzimas do metabolismo oxidativo, enquanto os indivíduos do inverno apresentaram coloração mais pálida e maior atividade enzimática associada ao estresse. Esses achados sugerem que as variações sazonais induzem ajustes fisiológicos e metabólicos, refletindo uma redistribuição das reservas energéticas de acordo com as condições ambientais. Tais respostas indicam a plasticidade adaptativa da espécie diante das flutuações ambientais características do Pantanal.

Palavras chave: Plasticidade fisiológica, Mudanças ambientais, Variações sazonais, Enzimas metabólicas e Coloração corporal.

Running-title:

Warming and Seasonality Effects on *Moenkhausia bonita* in the Pantanal

Introduction: The Pantanal is considered the world's largest floodplain and represents one of the ecosystems richest in aquatic biodiversity (Libonati *et al.* 2020; Caballero *et al.* 2025). The region's characteristic seasonality is marked by flood periods in summer and drought in winter, which directly influences habitat availability (Guerra *et al.* 2025), water quality, and the life cycle of fish, which constitute one of the most important groups for maintaining ecological balance and for the subsistence of local communities.

Temperature fluctuations, whether of natural or anthropogenic origin, to which this biome is exposed, can cause acute stress in aquatic organisms, while prolonged exposure to these conditions can lead to states of chronic stress, persisting for weeks or months *(*Stevens *et al.* 2017; Dorce *et al*. 2025). These temperature changes incessantly impose selective pressure on many organisms, resulting in phenotypic plasticity, particularly through the expression of different adaptive traits in response to variations in these environmental conditions.

In stressful situations such as temperature oscillations, excess reactive oxygen species oxidize and damage cellular lipids, proteins, and DNA, leading to their modification, often rendering them useless or inhibiting their normal function (Valko *et al*., 2007). avoid such consequences, it is crucial to ensure control over free radical production as well as maintain adequate levels of antioxidants.

Changes in animal behavior can often emerge as an important indicator of variations in external or internal factors (Berlinghieri *et al*. 2021). Concern for welfare applied to fish has grown considerably in recent years, and a better understanding of these animals' normal habits can favor the development of welfare indicators, associated with biochemical parameters of stress response (Diniz and Honorato 2012; Fabrizzi *et al.* 2025). The use of key welfare indicators in fish can aid in understanding the states of stress to which these animals are subjected (Honorato et al. 2024).

The Pantanal floodplain hosts a rich ichthyofauna. In the state of Mato Grosso do Sul, approximately eight species of the genus *Moenkhausia* are known, small characids widely distributed in the Paraguay River basin (Froehlich *et al.* 2017). *Moenkhausia bonita* (Benine, Castro & Sabino, 2004) is an abundant species, also recorded in other basins, such as the Amazon region. Individuals of this species are often found in schools of ten to thirty specimens, swimming near the water surface and among floating vegetation (Caldatto et al. 2023).

Even though it is not listed as a threatened species on the Red List of the Ministry of the Environment (Ordinance MMA No. 148/2022), studies on these animals are necessary, since environmental fluctuations caused by climate change and anthropogenic actions can affect different trophic levels and influence nutrient availability for the subsistence of these organisms, thereby compromising the species' maintenance in its natural environment (Froehlich *et al.* 2017, Caldatto *et al.* 2023).

This work aims to evaluate the morphological and biochemical responses of *Moenkhausia bonita* to seasonality and water warming in the Pantanal, highlighting how these fish respond morphologically and physiologically to the environmental fluctuations of the habitat in which they live.

Materials And Methods

Fish were collected in their natural environment in the Paraguay Mirim region (Figure 1) (18° 29' 23.55" S, 57° 24' 27.46" W). Specimens of *Moenkhausia bonita* were collected in the summer of 2023 and the winter of 2024.

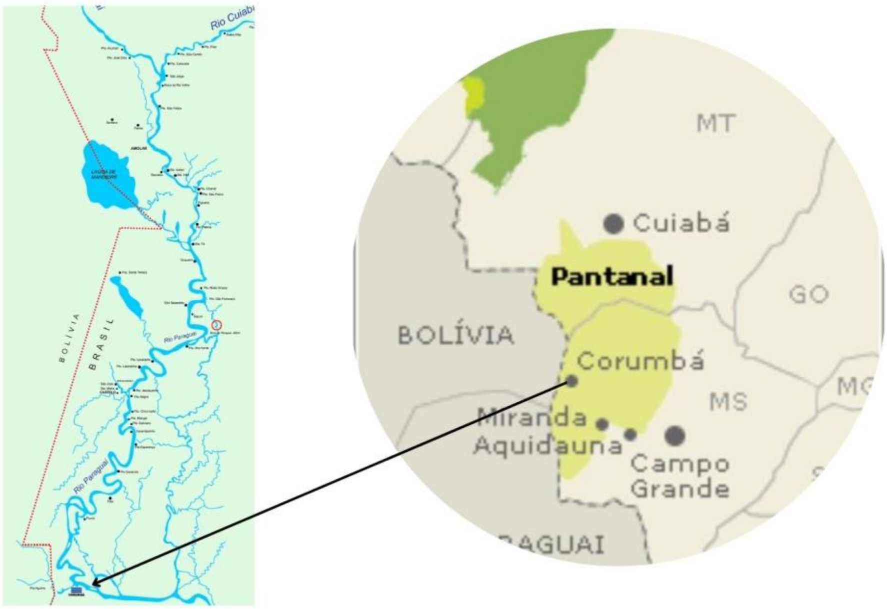


Figure 1: Map of the Paraguay River, highlighting the collection area used in the study.

Characterization Of The Sampling Environment

Water Quality: Water temperature was analyzed during both sampling periods (December 2023 and June 2024) at three distinct points. The variables temperature (°C), electrical conductivity (EC), and dissolved oxygen (DO) were measured using a digital multiparameter meter (Godoy et al. 2021). The hydrogenionic potential (pH) was determined using a portable digital pH meter (Hydroponic Quality Tester, model B0CT3JKR18). The variable Nitrite (NO_2, ppm), Ammonia (NH_3, ppm) and Nitrate (NO_3, ppm) didn't present detectable values.

Table 1 Water quality parameters observed in the Paraguay Mirim region, Municipality of Corumbá (MS), during December 2023 and June 2024.

Variables	Summer	Winter
Temperature (°C)	30,87±1,79	26,67±0,45
pH	7,11 ± 0,46	7,60±0,43
Conductivity (µS cm^{-1})	76,67 ± 46,23	110,33±47,27
Dissolved Oxygen (mg L^{-1})	4,09 ± 0,35	5,24±0,41
Transparency (cm)	11,33 ± 16,17	20,67±16,17

Rainfall Characterization: Rainfall indices for the months in which collections were carried out and for the years 2023 and 2024 were collected from databases available for public consultation at the National Institute of Meteorology (INMET). The incidence of fire hotspots was verified through the National Institute for Space Research (INPE).

The data presented by the National Institute of Meteorology (INMET) and the Secretariat of Environment, Development, Science, Technology and Innovation of Mato Grosso do Sul (SEMADESC) indicate that the total accumulated precipitation in 2024 was approximately 25% lower than the historical average, with annual values close to 700 mm, Reflecting a period of prolonged drought and water deficit (Table 2).

Tabela 2: Average rainfall index observed in the Paraguay Mirim region, Municipality of Corumbá (MS), for the periods of December (2023) and June (2024).

Location (Cravo Vermelho)	**Period**	**Mean precipitation ± SD (mm/day)**	**Total (mm)**	**Index (%)**
Base de Corumbá	Dec/23	4,81 ± 16,47	154	100
Base de Corumbá	Jun/24	1,88 ± 7,30	62	40,3

Biological Sample Collection: A total of 60 specimens of *Moenkhausia bonita* were collected. The fish were euthanized with eugenol (Honorato *and* Nascimento 2016) and measured with a digital caliper by the same observer to obtain weight, total length (measured from the mouth to the end of the caudal fin), standard length (measured from the mouth to the beginning of the caudal fin), height (measured horizontally in front of the dorsal fin and behind the pelvic fin), width (measured laterally behind the pectoral fins), and head length (measured from the mouth to the end of the operculum). The results were used to verify morphometric correlations (Melo *et al*. 2024).

Enzymatic Activity: Whole specimens of *Moenkhausia bonita* were subjected to a grinding process and homogenized with sodium phosphate buffer (glycerol v/v in 20mM sodium phosphate buffer and 10mM Tris – pH 7.0) in a Potter-Elvehjem type homogenizer. Subsequently, this sample was centrifuged at 4 ºC for three minutes at 600 x *g*, and the supernatant was subjected to a second centrifugation for eight minutes at 6000 x.

For the analysis of metabolic enzymes, the homogenate supernatant was used for the enzymatic assays of alanine aminotransferase (ALT) and aspartate aminotransferase (AST). The measurements of the activity of these enzymes were determined by a modification of the method of (Reitman *and* Frankel 1957). Sample readings were performed by spectrophotometry (semi-automatic spectrophotometer Bioplus S-200) using the appropriate wavelength for each test. Glucose parameters were measured in the samples (Trinder 1969).

The antioxidant activity of the liver was assessed through the antioxidant enzymes superoxide dismutase (SOD) and catalase (CAT). Superoxide dismutase (SOD) was tested by pyrogallol autoxidation, which is inhibited in the presence of SOD (Beutler 1984). Absorbance readings were performed at 420 nm, considering that 1.0 U inhibits 50% of pyrogallol autoxidation. Catalase (CAT) activity was tested by reading the decay of Hydrogen Peroxide (H_2O_2) at 230 nm (Beutler, 1984). One unit of CAT was defined as the amount of enzyme required for the oxidation of 1.0 µmol of H_2O_2 min^{-1}, and the molar absorptivity used was (H_2O_2) $\varepsilon\lambda 230 = 0.071\ mM^{-1}\ cm^{-1}$. Protein was determined using Bradford reagent against a standard BSA solution (Bradford 1976).

Color Analysis: The color intensity of the specimens was verified using photographs taken during collection and analyzed using specific software to capture color intensity (Image Pro

Plus). The verification scales (Fig. 2) were the RGB parameters: Red, Green, and Blue (Salaah 2021, Sabrina *et al.* 2023). The color was measured utilization the software LAB Color Chart v2 (Teixeira *et al.,* 2024).

Figure 2: *Detail of the color analysis locations for Moenkhausia bonita. A: Head coloration (RGB). B: Dorsal coloration (RGB). C: Caudal fin coloration.*

Statistical Analysis: Data normality was verified using the Shapiro-Wilk test. Once normality was confirmed, data from the summer and winter periods were subjected to analysis of variance (ANOVA); in cases of differences, Student's t-test was applied ($p < 0.05$). For the analysis of Pearson correlation ($p < 0.01$) between morphometric characteristics, 57 specimens were used.

Multifactorial Analysis (Kiers, 1991) was used to assess the correlation between mixed variables qualitative (summer and winter) and quantitative (enzymatic data). This technique allows for the reduction of data dimensionality by performing a linear combination to discard components with lower variation, thereby highlighting the most influential variables. The FMAD analyses were performed in R software (R Core Team, 2022) using the FactoMineR (Husson *et al*., 2024) and factoextra (Kassambara, 2020) packages.

RESULTS:

Fish collected in the summer period were significantly ($p < 0.05$) smaller compared to those collected in the winter period (Table 3). An increase in coloration was observed in fish collected in the summer, as assessed by RGB coordinates. We observed an increase in the coloration of the dorsal region and head, showing higher values in the G, B, and R patterns (green, blue, and red, respectively) ($P < 0.05$) in summer.

Table 3: *Body morphometry and coloration of Moenkhausia bonita specimens collected during summer/2023 and winter/2024 in the Paraguay Mirim region, Municipality of Corumbá (MS).*

Variáveis	**Verão (média ± DP)**	**Inverno (média ± DP)**	**CV %**	***p-Valor***
Total length (mm)	$23,609 \pm 2,666^{b}$	$27,648 \pm 3,121^{a}$	11,29	*0,0001*
Standard length (mm)	$18,952 \pm 2,019^{b}$	$22,863 \pm 2,437^{a}$	10,66	*0,0001*
Height (mm)	$5,273 \pm 0,986^{b}$	$6,065 \pm 1,134^{a}$	18,73	*0,013*
Head circumference (mm)	$4,884 \pm 0,694^{b}$	$5,965 \pm 0,849^{a}$	14,21	*0,0001*
Dorsal Coloration				
Blue	$114,328 \pm 23,90^{a}$	$82,140 \pm 17,18^{b}$	20,92	*0,0002*
Green	$121,646 \pm 23,63^{a}$	$93,416 \pm 18,12^{b}$	19,41	*0,0013*
Red	$110,447 \pm 18,16^{a}$	$86,719 \pm 14,27^{b}$	16,45	*0,0234*
Head Coloration				
Blue	$108,294 \pm 19,41^{a}$	$62,651 \pm 10,95^{b}$	17,94	*0,0001*
Green	$116,483 \pm 20,39^{a}$	$76,989 \pm 13,47^{b}$	17,50	*0,0005*
Red	$114,428 \pm 22,48^{a}$	$96,504 \pm 18,93^{a}$	19,65	*0,1413*
Caudal Coloration				
Blue	119.8 ± 14.0^{a}	155.6 ± 12.5 a	12.1	*0,0001*
Green	136.0 ± 14.1^{b}	72.0 ± 10.8 b	20,90	*0,0005*
Red	116.8 ± 12.5^{b}	59.8 ± 11.2 b	17,94	*0,0005*

* Means with distinct superscript letters report significant differences by Student's t-test ($p < 0.05$).

Head coloration showed a* and b* values close to the center of the diagram, indicating low saturation and subtle, slightly yellowish tones (Figure 3). The dorsal region was distributed more broadly within the color space, forming a more dispersed cluster positioned towards the green-blue quadrant, suggesting greater chromatic variability among individuals. Finally, the tail clearly differed from the other regions, exhibiting high positive a* values and negative b* values, placing it in the magenta quadrant of the CIELab space. This region also showed the lowest L* values, indicating lower luminosity and greater chromatic intensity. Collectively, these results demonstrate that the tail is the most saturated and contrasting structure, while the head and dorsal region exhibit more neutral and less vivid colorations.

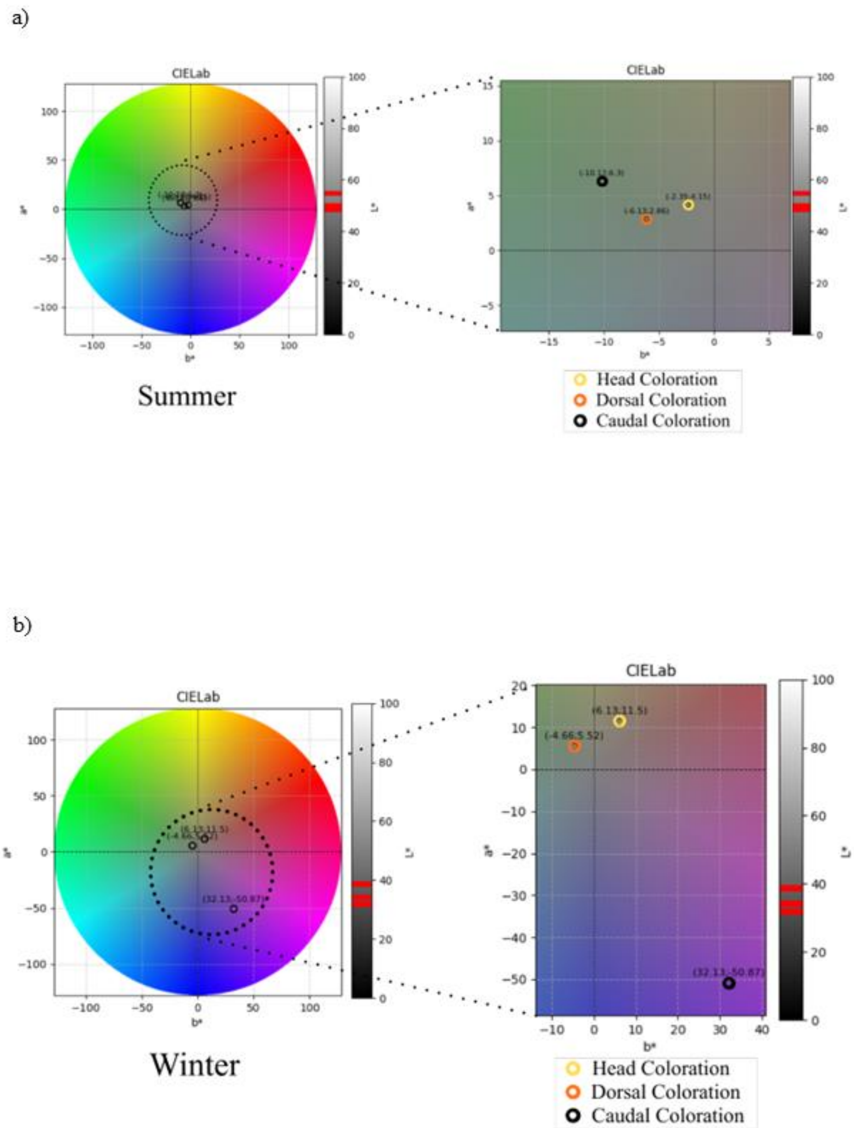


Figura 3: Distribution of color values from the head, dorsal, and caudal regions in CIELab space. The left panel shows the sample locations relative to the hue circle, while the right panel provides a detailed view of the area where the values are concentrated.

The Pearson correlation analysis (Table 4), performed to evaluate the relationship between weight, standard length, total length, height, width, and head length of *Moenkhausia bonita* fish, revealed positive correlations among the variables. The correlations between total length and standard length (0.94) and height (0.82) were the most significant, regardless of the sampling season. However, the correlation between height and head circumference was stronger in winter fish.

Table 4. Pearson correlation between morphometric variables of Moenkhausia bonita specimens captured during the summer/2023 and winter/2024 periods in the Paraguay Mirim region, Municipality of Corumbá (MS).

		TL	SL	H	HC
Summer	Total length (TL)	1	0,9377*	0,8077*	0,6033*
	Standard length (SL)		1	0,8318*	0,5378*
	Height (H)			1	0,3790*
	Head circumference (HC)				1
Winter	Total length (TL)	1	0,9373*	0,8833*	0,4995*
	Standard length (SL)		1	0,8586*	0,5766*
	Height (H)			1	0,5009*
	Head circumference (HC)				1

Fish collected during the winter period showed higher hepatic activity values ($p > 0.05$) compared to fish collected in summer (Figure 4a). The activities of oxidative metabolism enzymes and glucose were also higher in the winter period ($p > 0.05$) compared to fish collected in summer (Figure 4b).

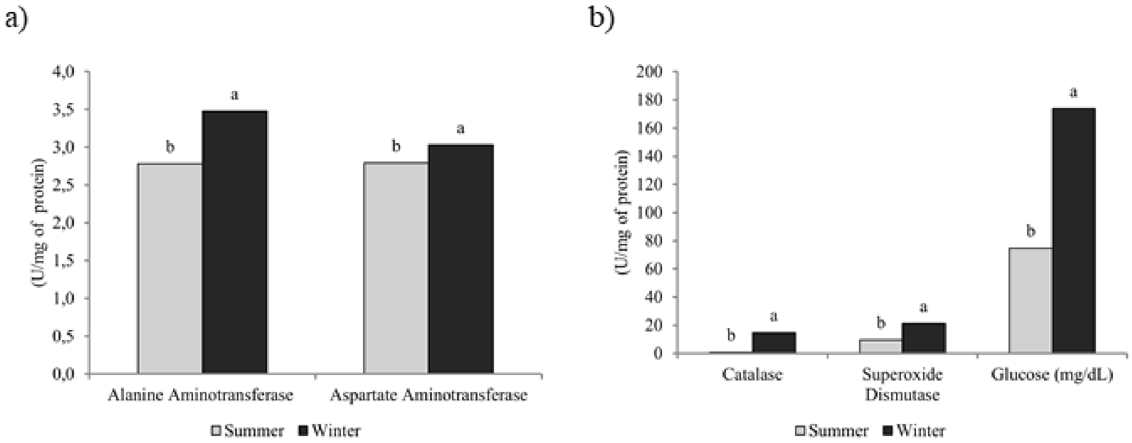
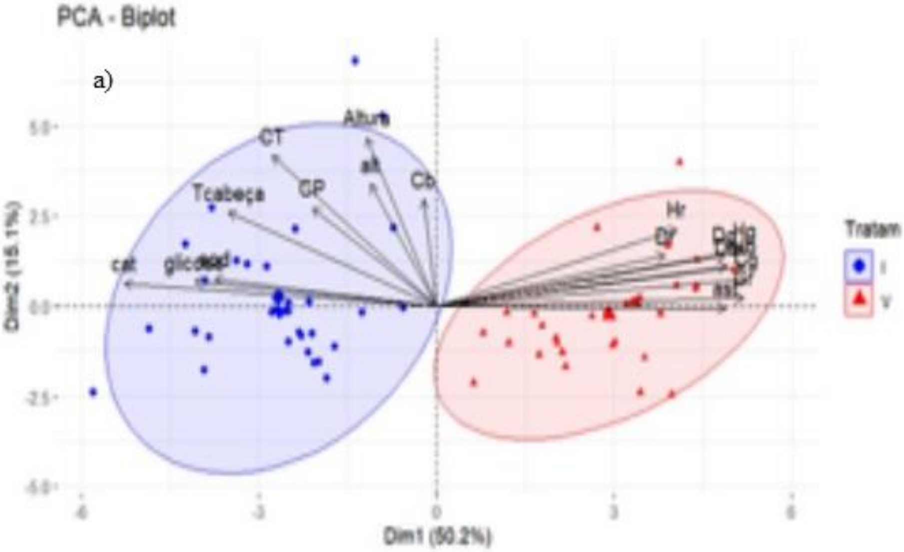


Figure 4: Activity of hepatic metabolism enzymes (a) and activity of oxidative metabolism enzymes and glucose (b) in *Moenkhausia bonita* specimens captured during the summer/2023 and winter/2024 periods in the Paraguay Mirim region, Municipality of Corumbá (MS).

The principal component analysis demonstrates that fish collected in summer and winter form distinct groups (Figure 5a). For fish collected in winter, antioxidant activity and glucose are the most important components characterizing this group (Figure 5b). However, in summer, coloration predominates as the characterizing component.



b)

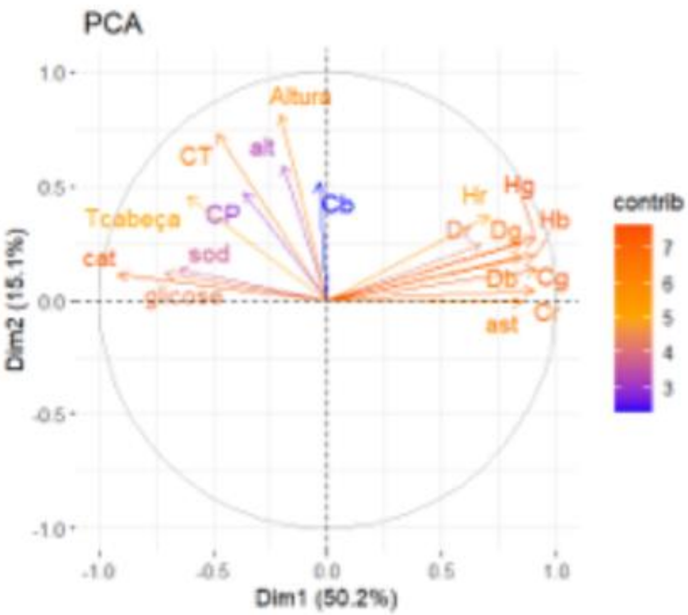


Figure 5: *Visualization of the multifactorial analysis - PCA. (A) Biplot (LM1.1) of Dimensions 1 and 2, where: red points represent the group collected in summer; blue points represent the group collected in winter. The rings correspond to the 95% confidence ellipses estimated using the mean of the treatments. The variance explained for each dimension is shown in parentheses. (B) Correlation of quantitative variables and their contributions within each dimension. Namely: Height (Altura), Total length (CT), Standard length (CP), Head length (Cb), Head size (Tcabeça), Hr: head red, Hg: head green, Hb: head blue, Dr: Dorso red, Dg: Dorso green, Db: Dorso blue, Cr: Caudal red, Cg: Caudal green, Cb: caudal blue, Sod: Superoxide dismutase (SOD), Cat: Catalase, Ast: Aspartate aminotransferase, Alt: Alanine aminotransferase, Glucose (glicose).*

Discussion: The results indicated that fish collected in the winter period exhibited higher values of hepatic activity, as well as higher activities of oxidative metabolism enzymes and glucose levels compared to fish collected during summer ($p > 0.05$). This pattern suggests a higher metabolic demand in the winter period, a time when this region was suffering from a high incidence of fires. These results demonstrated the notable phenotypic and physiological plasticity of *M. bonita*.

Winter fish, collected during a period of stress due to prolonged drought and high incidence of fires, which lead to increased sediments and toxins in the water, showed increased hepatic and oxidative metabolism activity (SOD and CAT enzymes) and elevated glucose, reflecting a higher metabolic demand and energy mobilization to cope with chemical and physiological stress. During this period, the scarcity of rains directly contributed to the increased incidence of fires in the biome. According to the Fire Program of the National Institute for Space Research (INPE), the Pantanal recorded approximately 6,800 heat foci in 2024, corresponding to about 17% of the total biome area affected by fires.

Fires can significantly alter water quality, increasing sediments, toxic products, and variations in oxygen availability, constituting an important environmental stressor for fish (Beakes *et al.* 2014). The increase in hepatic and oxidative metabolism activities observed in winter individuals may reflect adaptive responses involved in fish detoxification (Deboleto *et al*. 2024; Fabrizzi *et al.* 2025) and energy maintenance, allowing them to face the chemical and physiological stress imposed by the new environment. The elevation in glucose suggests that these animals undergo a mobilization of energy reserves to sustain these vital functions, being an important stress marker for fish under different circumstances (Taylor e Davis 2011).

Despite the higher metabolism observed in winter, fish from this season presented significantly larger sizes than those from summer ($p < 0.05$). This pattern indicates that, even when subjected to environmental stress, individuals were able to allocate sufficient energy for the growth process, possibly due to higher metabolic efficiency, availability of energetic resources, and more stable temperatures during winter (Canosa *and* Bertucci 2023). Similar results were observed under controlled conditions for Blue Tilapia (*Oreochromis aureus*), whose growth was significantly higher at milder temperatures, below 27°C (Salaah 2021).

In contrast, summer fish exhibited smaller body size, possibly due to the combination of high temperatures and lower oxygen availability, limiting factors for growth (Liu *et al.* 2022. Temperature is a critical environmental factor in fish ecology, significantly influencing their physiology and behavior (Dorce *et al*. 2025).

Positive correlations were observed in the morphometric variables of both seasons, indicating that the growth of different body structures occurred in an associated manner, presenting a strong relationship between total length, standard length, and body height. Understanding how phenotypic correlations occur in nature is considered important for implementing genetic improvement programs for species that may be of interest for commerce (Hilsdorf and Orfão 2011; Melo *et al*. 2024). In the observed species, correlations were slightly higher between height and length in winter, reflecting a better body condition and greater efficiency in the use of energetic resources during this period, consistent with the higher values of hepatic activity and oxidative metabolism enzymes observed.

Regarding the activities of selected metabolic enzymes in hepatic tissue, an increase was observed with decreasing temperature (Wen *et al.* 2017). Under temperature stress, the antioxidant defense system would inhibit excess oxyradical formation (Ye *et al*., 2016; Ren *et al.*, 2018). SOD and CAT generally act in a coordinated manner to ensure optimal protection against oxidative stress (Aliko *et al*. 2018). Endogenous antioxidant enzymes play a crucial role in eliminating harmful reactive oxygen derivatives, which were important indicators of antioxidant response in fish (Yang *et al*. 2018; Gauer *et al.* 2025). The metabolic stress caused by the modification of environmental temperature requires the organism to seek ways to adapt to the new conditions, thus reflecting in the increased activity of hepatic metabolism and the antioxidant system (Brambilla *et al.* 2025; Yang *et al.* 2018).

Fish coloration was also a determining point of variation. Animals collected in summer showed a significant increase in dorsal and head coloration, with higher values in the G (green), B (blue), and R (red) patterns ($p < 0.05$). This suggests that, under the less challenging environmental conditions of summer, fish may allocate energy to visual signals, such as coloration, which play an important role in intraspecific communication, sexual attraction, or camouflage (Eiji *et al*. 2004; Andrade *et al.* 2015)

Principal component analysis (PCA) was employed to identify which collected variables were most associated with physiological changes in fish between the evaluated seasons. The first component explained most of the total variance, showing a clear separation between seasonal groups. The main differences were observed in the results of enzymes related to oxidative metabolism and in the animals' color (RGB) values. This pattern suggests that seasonal changes influence both oxidative metabolism and coloration, reflecting physiological adjustments to environmental conditions.

The reported reproductive period for other members of this genus coincides with the collections made during summer (Eiji *et al*. 2004). The events preceding reproduction, coupled with environmental changes, constitute important factors for triggering various physiological changes, with coloration becoming a striking characteristic of species during this period. In winter, individuals are at the end of the reproductive period, which requires high physiological compensation to supply the effort of reproduction (Brambilla *et al.,* 2025).

Skin coloration is also associated with the antioxidant activity presented by fish (Porto *et al.* 2020; França *et al*. 2022; Dorce *et al.* 2024). Diet is a primary factor for color expression (Honorato *et al.* 2021) ; however, amino acid composition determines the metabolic pathways for color expression (Scardua *et al.* 2024) making food availability fundamental, since this species primarily feeds on small insects (Caldatto *et al.* 2023). It is noteworthy that during the wet season, the high incidence of rains promotes the restructuring of the entire food chain, favoring food availability (Eiji *et al*. 2004; Brambilla *et al.* 2025).

The principal components also suggest an inverse relationship between variables associated with coloration (RGB components) and indicators of metabolic activities, such as ALT, AST, and antioxidant enzymes (CAT and SOD). This suggests that increased metabolic activity and oxidative stress are associated with reduced color intensity in individuals. Such patterns may reflect a physiological trade-off (Garland, 2014), a mechanism described in biology as a way to direct energetically costly processes, such as the maintenance of pigments and phenotypic expression, towards the maintenance of vital functions, ensuring greater chances of survival (Faria *et al*. 2018; Rosenfeld *et al*. 2020).

The analysis of the overall results demonstrates an improvement in hepatic enzyme activity and biochemical parameters during the summer period. Higher temperatures, coupled with a lower incidence of environmental contaminants, favor fish health, indicating lower hepatic stress (Deniz *et al.* 2018). The activity of CAT and SOD enzymes is related to the removal of free radicals and the inhibition of reactive compounds from metabolism, delaying cellular damage (Godoy *et al.* 2024). Furthermore, these enzymes play a crucial role in modulating the immune system, improving hematological responses and reducing the effects of stress (Ota *et al*. 2019; Sawicki *et al*. 2020).

These findings highlight the physiological and adaptive plasticity of fish in the face of seasonal variations and environmental stresses. The integration between metabolism, growth, and coloration shows that fish flexibly adjust energy allocation, responding differently to fires and seasonal conditions, providing a broader understanding of adaptive strategies in natural environments subject to intense environmental disturbances.

Seasonal and thermal variations in the Pantanal significantly influenced the morphological and biochemical responses of *Moenkhausia bonita.* During the dry period, increased temperatures and reduced water quality were associated with heightened enzymatic activities and biochemical changes indicative of physiological stress. In contrast, during the rainy season, this species exhibited greater pigment expression and maintained tissue integrity, suggesting a more balanced metabolic state under favorable environmental conditions.

The results highlight the remarkable phenotypic and physiological plasticity of *M. Bonita*, demonstrating that these fish can flexibly allocate energy reserves by adjusting growth, metabolism, and coloration in response to varying environmental demands. Continuous monitoring of these parameters is essential to understand the impacts of seasonal variations and water warming on Neotropical ichthyofauna.

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Data Availability Statement

The data generated and analyzed during the development of this study are available from the corresponding author, Leticia Maria Albuquerque Conceição, upon reasonable request.

Artificial Intelligence Statement

The authors declare that no AI-assisted technologies were used in the preparation of this manuscript or in the creation of its figures.

Ethical Statement

The experiment was approved by the Animal Ethics Committee of the Federal University of Grande Dourados (UFGD), under protocol number 003/2019. SISGEN registration code: AA88DF1.

Conflicts of Interest

The authors declare that there are no conflicts of interest related to this manuscript.

Author Contributions

Leticia Maria Albuquerque Conceição: Writing – review & editing; Conceptualization; Investigation; Data curation; Visualization; Project administration.

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Figure 1: Map of the Paraguay River, highlighting the collection area used in the study.

Figure 2: Detail of the color analysis locations for *Moenkhausia bonita*. A: Head coloration (RGB). B: Dorsal coloration (RGB). C: Caudal fin coloration.

Figure 3: Distribution of color values from the head, dorsal, and caudal regions in CIELab space. The left panel shows the sample locations relative to the hue circle, while the right panel provides a detailed view of the area where the values are concentrated.

Figure 4. Activity of hepatic metabolism enzymes (a) and activity of oxidative metabolism enzymes and glucose (b) in *Moenkhausia bonita* specimens captured during the summer/2023 and winter/2024 periods in the Paraguay Mirim region, Municipality of Corumbá (MS).

Figure 5: Visualization of the multifactorial analysis - PCA. (A) Biplot (LM1.1) of Dimensions 1 and 2, where: red points represent the group collected in summer; blue points represent the group collected in winter. The rings correspond to the 95% confidence ellipses estimated using the mean of the treatments. The variance explained for each dimension is shown in parentheses. (B) Correlation of quantitative variables and their contributions within each dimension. Namely: Height (Altura), Total length (CT), Standard length (CP), Head length (Cb), Head size (Tcabeça), Hr: head red, Hg: head green, Hb: head blue, Dr: Dorso red, Dg: Dorso green, Db: Dorso blue, Cr: Caudal red, Cg: Caudal green, Cb: caudal blue, Sod: Superoxide dismutase (SOD), Cat: Catalase, Ast: Aspartate aminotransferase, Alt: Alanine aminotransferase, Glucose (glicose).

Table 1. Water quality parameters observed in the Paraguay Mirim region, Municipality of Corumbá (MS), during December 2023 and June 2024.

Table 2. Average rainfall index observed in the Paraguay Mirim region, Municipality of Corumbá (MS), for the periods of December (2023) and June (2024).

Table 3. Body morphometry and coloration of *Moenkhausia bonita* specimens collected during summer/2023 and winter/2024 in the Paraguay Mirim region, Municipality of Corumbá (MS).

Table 4. Pearson correlation between morphometric variables of Moenkhausia *bonita* specimens captured during the summer/2023 and winter/2024 periods in the Paraguay Mirim region, Municipality of Corumbá (MS).

CONSIDERAÇÕES FINAIS

As duas etapas desta dissertação convergem para um eixo estruturante: a qualidade ambiental como determinante do bem-estar, da estabilidade fisiológica e da sustentabilidade na produção de peixes ornamentais, especialmente em um contexto ecológico sensível como o Pantanal. A revisão sistemática demonstrou que o enriquecimento ambiental promove a expressão de comportamentos naturais, reduz indicadores de estresse e favorece a manutenção da homeostase, consolidando-se como componente essencial de sistemas produtivos tecnicamente eficientes e eticamente responsáveis.

No âmbito experimental, a análise do estresse oxidativo evidenciou que peixes provenientes de ambientes sujeitos às flutuações hidrológicas e térmicas características do Pantanal apresentam respostas metabólicas adaptativas, com ajustes nos mecanismos antioxidantes e na regulação do equilíbrio redox. Essa plasticidade fisiológica reflete a história evolutiva das espécies do bioma, moldadas por pulsos de inundação, variações sazonais extremas e dinâmicas ambientais complexas. Contudo, frente ao aumento da pressão antrópica e à intensificação de eventos climáticos extremos, compreender os limites dessa capacidade adaptativa torna-se fundamental.

A integração entre enriquecimento ambiental e conhecimento dos mecanismos de resposta ao estresse fornece base científica para posicionar a aquicultura como ferramenta de conservação da biodiversidade pantaneira. Sistemas de produção bem estruturados podem reduzir a captura de indivíduos na natureza, favorecer a reprodução controlada de espécies nativas e contribuir para a manutenção de estoques genéticos. Além disso, a criação em ambientes enriquecidos aproxima as condições de cultivo das exigências ecológicas naturais, aumentando a viabilidade de programas de conservação ex situ e potencialmente apoiando estratégias futuras de repovoamento ou manutenção de populações ameaçadas.

Nesse contexto, a aquicultura deixa de ser apenas atividade produtiva e passa a assumir papel estratégico na conservação do Pantanal, conciliando geração de renda, valorização de espécies nativas e proteção da biodiversidade. Assim, esta dissertação contribui para o avanço de uma abordagem integrada em que bem-estar animal, fisiologia adaptativa e conservação ambiental são dimensões interdependentes de um mesmo sistema socioecológico.