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REVIEW ARTICLE

Tadpoles as Bioindicators of Aquatic Ecosystem Health: A Systematic Review of Water Quality and Land Use Interactions on Tadpole Assemblages

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ABSTRACT

Amphibian populations are in global decline, with 41% of species considered threatened, driven by habitat loss, land use change, climate change and diseases, particularly chytridiomycosis. Larval stages are confined to aquatic environments making tadpoles reliable bioindicators of ecosystem health due to high sensitivity to both water quality and surrounding land use. This systematic review synthesizes evidence from 58 studies published between 2005 and 2025 that examined the effects of land use and water quality characteristics on anuran tadpole assemblages. Following PRISMA 2020 guidelines, a structured literature search was conducted across Web of Science, Scopus and Google Scholar in December 2025. Studies were synthesized narratively across four thematic objectives: (i) land use effects on breeding habitat suitability, (ii) water quality and pollutant exposure, (iii) tadpole density and breeding pool dynamics and (iv) tadpole deformities and sublethal effects. Results indicate that agricultural expansion and urbanization modify breeding habitats, reduce tadpole density and increase malformation rates, whereas water quality stressors, including eutrophication, contaminant loading and hydroperiod variability, were consistently linked to developmental abnormalities. These findings highlight the importance of breeding habitat management for amphibian conservation. We recommend prioritizing protection and restoration of natural ponds, mitigating agricultural runoff and standardizing monitoring protocols. This synthesis provides a framework for conservation strategies and identifying key research gaps in amphibian larval ecology.

1 | Introduction

Amphibian populations are in global decline, with 41% of species considered threatened by the International Union of Conservation of Nature (IUCN) Red List of Threatened Species (IUCN 2024; Luedtke et al. 2024). Habitat loss and disease, particularly chytridiomycosis, are the primary causes of decline (Luedtke et al. 2024; Scheele et al. 2019). Human activities, including expansion of infrastructure, agricultural land use, vegetation destruction and climate change, have led to fragmentation and loss of habitats, directly impacting species distribution and survival (Pounds et al. 2006; Song et al. 2021; Yaman and Van Huynh 2024; Zhao et al. 2022). Amphibians are highly sensitive to environmental changes, and contaminants on both terrestrial and aquatic ecosystems make them ideal indicators of ecosystem health (Aravind et al. 2024; Díaz-García et al. 2017; Kıraç et al. 2022; Lawler et al. 2010). Their complex life cycles and exposed skin make them susceptible to climate change and pathogen invasions (Hayden Bofill and Blom 2024; Taylor et al. 2021). Larval stages are confined to aquatic environments which are exposed to increased human disturbance; therefore, they are directly influenced by breeding pool characteristics, hydroperiod, physicochemical parameters and surrounding land use (O'Hara et al. 2024;

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Waldock et al. 2024). Artificial habitats can support some amphibian species. However, altered hydrology, ecological traps and agrochemical runoff can lower survival rates and reduce biodiversity (Băncilă et al. 2023; Garnett et al. 2013).

Understanding larval-stage responses is critical because early-life exposure to environmental stressors can determine survival trajectories and long-term population persistence. Despite growing recognition of tadpoles as sensitive bioindicators, the evidence base remains fragmented across geographic contexts and study designs. A systematic synthesis of this literature is needed to identify research gaps, evaluate the strength of evidence and inform conservation strategies targeting breeding habitats. Following the 2005 Millennium Ecosystem Assessment, which led to a global increase in freshwater biodiversity monitoring, there has been a substantial growth in studies examining larval amphibian responses to land use and water quality (Millennium Ecosystem Assessment 2005). This review addresses the need for synthesis by evaluating published studies on the relationship between adjacent land use, water quality characteristics and larval-stage responses in anurans. Specifically, this review aims to (i) synthesize evidence on breeding habitat characteristics across different land use contexts; (ii) evaluate reported water quality parameters and pollutant effects on tadpole assemblages; (iii) assess documented patterns in tadpole density across breeding pool types; and (iv) characterize reported malformation rates and sublethal effects associated with contaminant exposure. By synthesizing evidence across 58 studies, this review provides an integrated assessment of larval responses to anthropogenic disturbance and identifies priorities for future research and conservation planning.

2 | Materials and Methods

2.1 | Literature Search Strategy

A systematic literature search was conducted in December 2025 to identify peer-reviewed studies examining tadpole ecology, anuran breeding habitats, water quality and pollutant effects on larval amphibians, covering the period of 2005–2025. The start year of 2005 was selected to align with the publication of the Millennium Ecosystem Assessment, which marked a significant increase in systematic freshwater biodiversity monitoring and standardized reporting of amphibian habitat responses globally (Millennium Ecosystem Assessment 2005). Three electronic databases were searched: Web of Science Core Collection, Scopus and Google Scholar (used as a supplementary source to capture additional grey literature and studies not indexed in the primary databases).

In Web of Science Core Collection, the search was conducted in the Topic field (TS=), which covers titles, abstracts, author keywords and Keywords. The following Boolean search string was applied:

> TS= (“anuran“ OR “frog“ OR “tadpole“) AND TS= (“land use“ OR “agriculture“ OR “urbanization“) AND TS= (“water quality“ OR “pollutant“ OR “contaminant“) AND TS= (“tadpole deformities“ OR “sublethal effects“).

In Scopus, the equivalent search was applied to Title, Abstract and Keywords fields (TITLE-ABS-KEY) using the same Boolean structure. Google Scholar was searched using the same keyword combinations entered as a free-text query. Publication date filters were applied to restrict results to 2005–2025 in all databases. The searches returned 38 records from Web of Science, 52 from Scopus and 63 from Google Scholar, yielding 153 total records prior to duplicate removal.

2.2 | Inclusion and Exclusion Criteria

Studies were considered eligible if they focused on tadpoles or anuran breeding habitats and reported quantitative or qualitative findings relevant to at least one of the four review objectives: (i) land use impacts on breeding habitat suitability, (ii) water quality and pollutant effects on larval amphibians, (iii) tadpole density as an indicator of breeding habitat quality or (iv) tadpole deformities and sublethal effects. Only studies published in peer-reviewed journals in the English language were included.

Studies were excluded if they were non-peer-reviewed publications, conference abstracts, editorials or theses or if full text was unavailable. Studies focused solely on adult amphibians outside of breeding contexts were also excluded, as were laboratory-based toxicological studies that lacked ecological field context and studies that did not assess land use change or water quality variables. Screening was conducted in two stages: first at the title and abstract level to identify potentially relevant studies, followed by full-text assessment for eligibility confirmation.

2.3 | Study Screening and Selection

Following the database searches, all 153 retrieved records were compiled, and 29 duplicate records were removed, yielding 124 unique records for screening. Title and abstract screening excluded a further 39 records that did not meet the inclusion criteria, leaving 85 records for full-text assessment. Of these, 27 were excluded after full-text review: 12 were not relevant to the review objectives, 9 lacked sufficient ecological context (e.g., purely laboratory toxicological studies), and 6 did not report tadpole-specific outcomes. This process resulted in 58 studies being included in the final synthesis. A PRISMA 2020 flow diagram illustrating the complete screening process is provided in Figure 1.

2.4 | Data Extraction

From each included study, the following information was extracted: authors and year of publication; study location and geographic region; study design (field survey, laboratory experiment, mesocosm study or biomarker-based assessment); primary objective or thematic focus; and relevant outcome measures including tadpole abundance, developmental rates, deformity prevalence, water chemistry parameters and pollutant concentrations.

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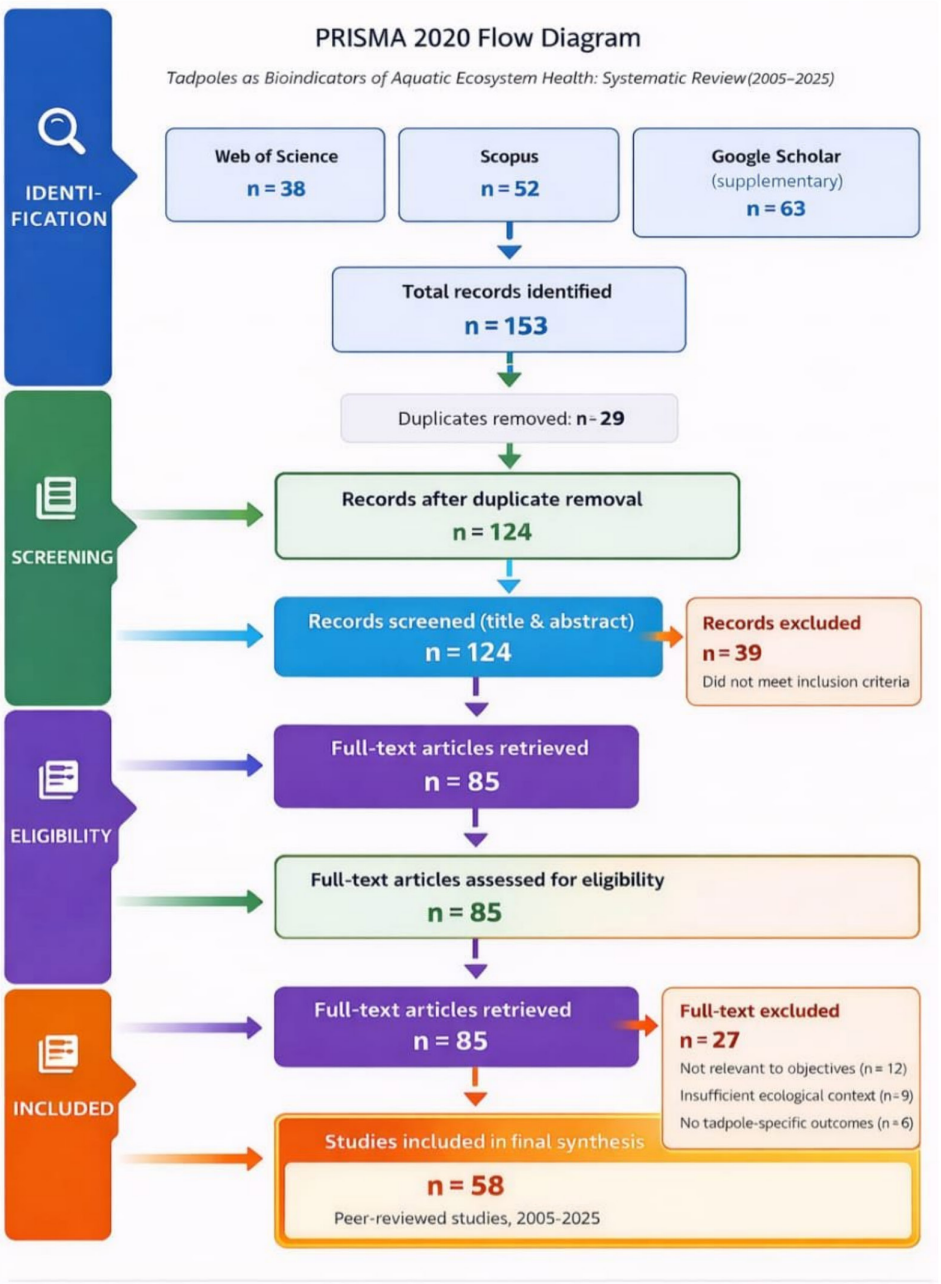

FIGURE 1 | PRISMA flow diagram showing study selection for the systematic review (2005–2025).

Studies were assigned to one or more of the four thematic categories based on their primary outcomes.

2.5 | Data Synthesis

A narrative synthesis approach was adopted, as the heterogeneity of study designs, geographic contexts and outcome measures hindered formal meta-analysis. Studies were grouped according to the four thematic objectives and synthesized by summarizing patterns of findings within each theme. The distribution of studies across thematic objectives is presented in Figure 2, and temporal trends in research output are visualized in Figures 3–5.

3 | Results

3.1 | Study Selection and Characteristics

A total of 58 studies published between 2005 and 2025 met the inclusion criteria. The included literature examined the influence of land use change, water quality degradation, hydroperiod variation, contaminant exposure and larval density on anuran breeding habitats and tadpole development. Studies were geographically distributed across temperate and tropical regions and employed a range of methodological approaches including field surveys, laboratory exposure experiments, mesocosm studies and biomarker-based assessments. Each study was categorized into one or more of four primary thematic objectives during data

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extraction: (i) land use and breeding habitat suitability ($n = 18$, 31%); (ii) water quality and pollutant exposure ($n = 15$, 26%); (iii) tadpole density and breeding pool dynamics ($n = 10$, 17%); and (iv) deformities and sublethal effects ($n = 15$, 26%). The distribution of studies across these objectives is presented in Figure 2.

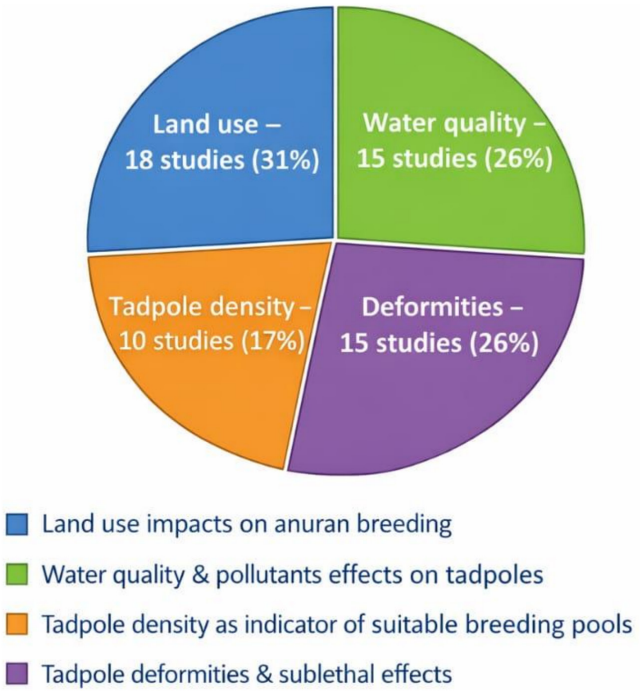

FIGURE 2 | Distribution of studies across these objectives.

3.2 | Temporal Trends in Research Output (2005–2025)

An overall increase in the number of studies focused on anuran breeding ecology and tadpole development was observed over the review period (Figure 3), reflecting growing scientific interest in larval amphibian responses to environmental stressors. Annual publication output was relatively low between 2005 and 2012, followed by a gradual increase from 2013 onwards, with a notable peak after 2020. Studies examining physicochemical water quality parameters dominated the literature throughout the entire review period (Figure 4), whereas research specifically focused on tadpole deformities and sublethal effects grew gradually before peaking around 2022 and sustaining elevated output thereafter. This temporal pattern suggests increasing scientific attention towards sublethal stressors and emerging contaminants such as microplastics in recent years.

3.3 | Influence of Land Use on Anuran Breeding

Land use was consistently associated with alteration of anuran breeding habitats and anuran larval assemblages. Agricultural expansion and exotic reforestation systems were associated with reduced larval abundance and shifts in community structure (Machado et al. 2012; Moreira et al. 2021; Saccol et al. 2017; da Silva Alves Saccol et al. 2022). Urbanization and agricultural activities were similarly identified as primary drivers of water quality degradation, particularly through runoff (Tong et al. 2023; Wang et al. 2024).

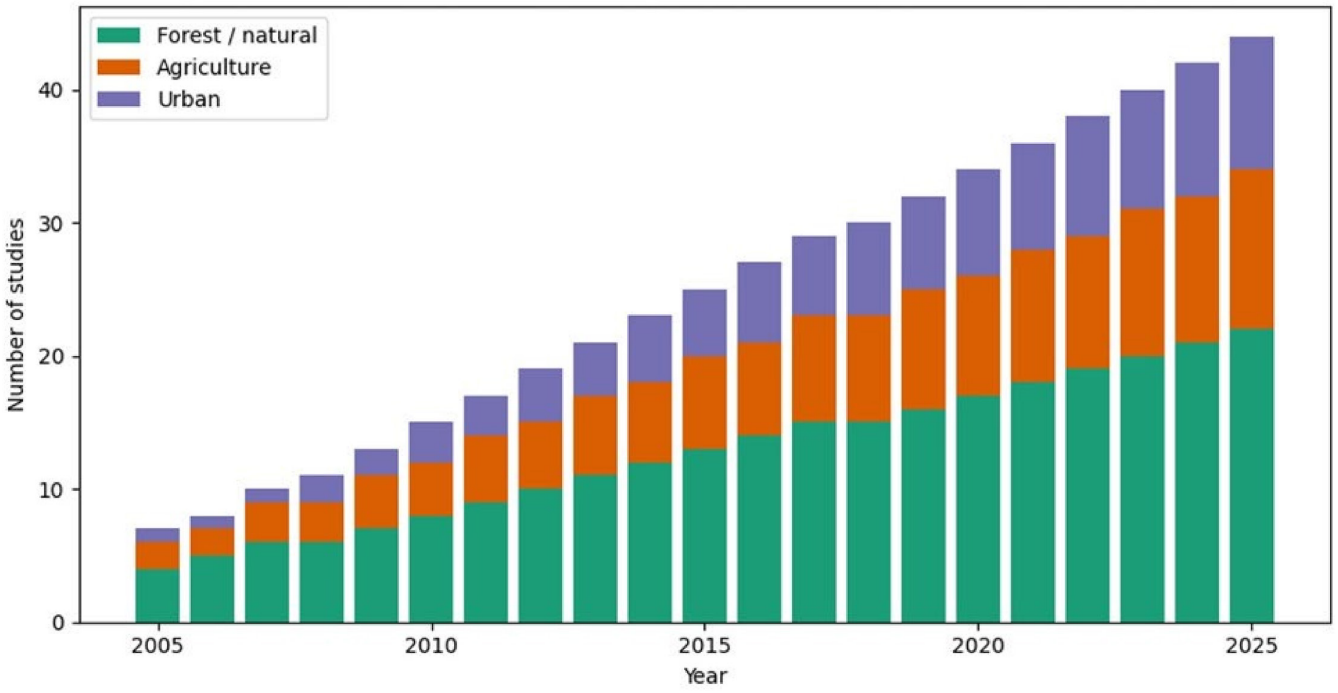

FIGURE 3 | Temporal trends in land use research within amphibian breeding pools (2005–2025).

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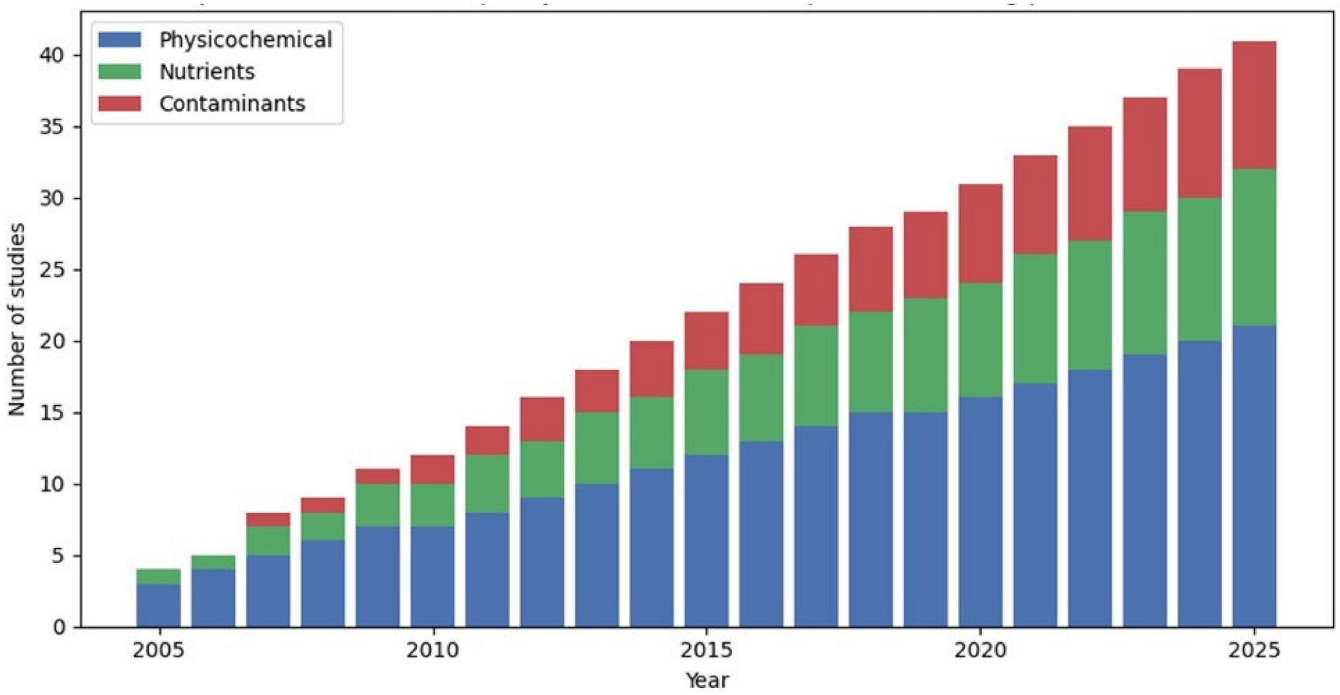

FIGURE 4 | Temporal trends in water quality research within amphibian breeding pools (2005–2025).

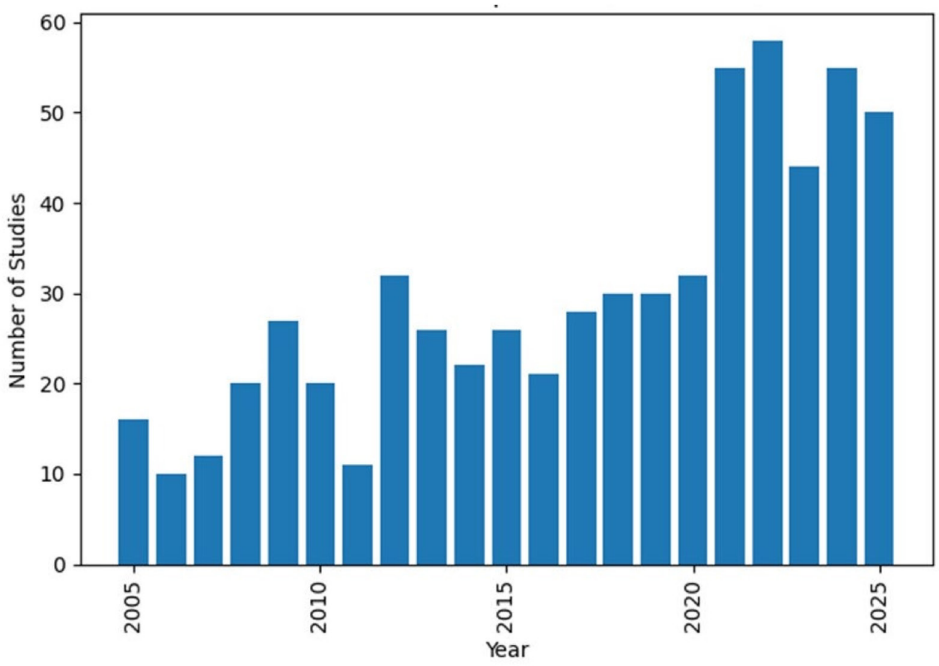

FIGURE 5 | Number of studies per year (2005–2025).

Changes in land use also modified physical characteristics of breeding habitats. Urbanization was associated with modified hydroperiods, reduced canopy cover and altered water chemistry with studies reporting early breeding phenology in urban (Liu et al. 2022). Agricultural landscapes are potentially linked to increased surface temperatures, which can alter thermal conditions within breeding habitats (Lembrechts et al. 2019; Schmidt et al. 2019; Tian et al. 2020).

Hydroperiod alteration also influenced larval development with climate-related changes associated with reduced precipitation and shortened hydroperiods, which were widely documented (Fay et al. 2016; Tasker et al. 2022; Xu et al. 2024). However, species responses to hydroperiod variation were diverse (Richter-Boix et al. 2011; Tejedo et al. 2010), with some exhibiting accelerated larval development in drying habitats and others experiencing reduced size at metamorphosis or decreased

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survival (Brannelly et al. 2019; Gervasi and Foufopoulos 2008; Koprivnikar et al. 2014; Ohmer et al. 2021).

3.4 | Impacts of Water Quality and Pollutants

Water quality emerged as a key driver of breeding habitat suitability and larval condition. Nutrient enrichment associated with agricultural runoff alongside higher temperatures was commonly associated with eutrophication, algal blooms and reduced dissolved oxygen levels (Woolway et al. 2022; Zhai et al. 2014).

In addition to nutrients, heavy metals, nitrate compounds and pesticide residues were frequently examined in laboratory and field studies. Exposure to heavy metals, nitrate compounds and pesticides were associated with endocrine disruption, oxidative stress, delayed or accelerated metamorphosis and impaired immune responses (Gao et al. 2025; Jarvie et al. 2025).

Microplastic exposure was increasingly a studied stressor, particularly in recent studies. This exposure was associated with altered growth, histopathological damage, behavioural changes and reduced survival (Bacchetta et al. 2021; Boyero et al. 2020; da Costa Araújo et al. 2020; Ruthsatz et al. 2022).

3.5 | Tadpole Density and Breeding Pool Suitability

Breeding pool characteristics strongly influenced larval occurrence and developmental outcomes (Pettitt et al. 2018; Touchon and Worley 2015). Studies examining breeding site selection identified species-specific preference for hydroperiod length, vegetation structure and predator presence (Brown et al. 2010; Lin et al. 2008; Pettitt et al. 2018; Poelman and Dicke 2007; Rojas 2014; Schulte et al. 2011; von May et al. 2009).

Hydroperiod represents a crucial trade-off in breeding pool suitability. Ephemeral ponds were associated with reduced predation pressure but increased desiccation risk (Brown et al. 2010; Summers and Tumulty 2014). Permanent ponds supported multiple species but exhibited higher predator densities and competitive interactions (Mathwin et al. 2021; Mogali et al. 2016, 2017; Ringler et al. 2018; Schulte et al. 2011).

Larval density also influenced developmental outcomes. Several studies reported inverse relationship between larval density, growth and metamorphic success, with lower densities associated with larger size at metamorphosis and shorter larval periods (Brannelly et al. 2025).

3.6 | Tadpole Deformities and Sublethal Effects

Multiple studies documented morphological deformities and physiological impairments in tadpoles exposed to environmental contaminants including heavy metals and water quality stressors. Chronic lead exposure was associated with malformations in *Bufo gargarizans*, including tail and fin abnormalities, abdominal oedema, axial flexures and reduced growth (Chai et al. 2017). Lead exposure also affected development, metamorphosis and skeletal ossification in *B. gargarizans* and *Pelophylax nigromaculatus*, with responses varying across exposure concentrations (Huang et al. 2014; Yang et al. 2019). Nitrate and ammonium exposure similarly affected larval growth and survival, with responses varying according to concentration and developmental stage (Balangoda et al. 2018; Garriga et al. 2017).

Sublethal effects extended beyond external morphology. Lead exposure was associated with changes in thyroid gland development, including follicular-cell hyperplasia and colloid depletion, whereas microplastic exposure produced hepatotoxic effects and altered gut microbial communities (Chai et al. 2023; da Costa Araújo et al. 2020; Yang et al. 2019). Microplastic exposure was also associated with increased susceptibility of amphibian larvae to *Batrachochytrium dendrobatidis* (Bosch et al. 2021).

4 | Discussion

This systematic synthesis demonstrates that tadpole responses are shaped by land use change, hydroperiod alteration and water quality degradation.

Agricultural intensification modifies both physical and chemical characteristics of breeding habitats (Gillespie et al. 2020; With et al. 2024), whereas urbanization and reduced precipitation modify hydroperiods favouring fast developing species while disadvantaging those with slower development rates (Moreira et al. 2020). These suggest that land use change can affect tadpole assemblages through alteration of breeding habitats, hydroperiod and deterioration of water quality.

Water quality degradation was linked to land use to larval responses. Nutrient enrichment and contaminant loading associated with agricultural runoff introduced heavy metals, nitrate compounds and pesticides lowered dissolved oxygen and affected both endocrinal and cell functioning, leading to increased mortality (Gao et al. 2025; Jarvie et al. 2025). Contaminated water led to thyroid disruption and altered developmental timing (Balangoda et al. 2018; Garriga et al. 2017; Huang et al. 2014; Yang et al. 2019). These responses demonstrate that tadpoles are early bioindicators of habitat degradation and contaminant exposure.

Beyond water chemistry, breeding habitat characteristics influence larval outcomes. Ephemeral ponds may reduce predation, but they increase desiccation risks, whereas permanent ponds provide longer hydroperiods but expose tadpoles to competition and predators (Gould et al. 2019; Pintar and Resetarits 2020; Stein and Blaustein 2015; Valdez 2020), thus suggesting ecological consequences are influenced by modifications of breeding habitats.

Within altered breeding habitats, density-dependent processes and predator–prey dynamics also influenced tadpole breeding success (Lebreton and Gimenez 2013; Ousterhout and Semlitsch 2016). Lower densities were associated with larger size at metamorphosis and shorter larval periods (Brannelly et al. 2025). However, tadpole responses differed across species

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or environmental contexts with habitat specialists occupying narrow ecological niches compared to generalists (Griffin and Sultan 2011; Klaus and Noss 2016), making them vulnerable to breeding habitat conditions.

5 | Conclusion and Recommendations

This systematic review of 58 studies demonstrates that anuran tadpole density and malformation rates are strongly influenced by surrounding land use and water quality characteristics. Agricultural expansion and infrastructure development modify habitats reducing tadpole abundance and increasing developmental abnormalities, whereas artificial ponds with favourable physicochemical conditions can support larval survival. Water quality parameters, particularly nutrient enrichment, pollutants and hydroperiod variation, bridge these responses, highlighting tadpoles' sensitivity as bioindicators. Conservation efforts should prioritize the protection and restoration of natural breeding habitats, management of agricultural runoff and continuous monitoring of water quality parameters to mitigate malformation risks. Future research should adopt standardized methodologies to assess larval-stage responses across diverse environmental contexts, enabling more robust site comparisons and evidence-based management strategies.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

This article is a review of previously published studies, and no original data were generated or analysed.

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