





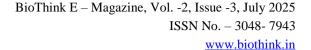
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Abstract

Herbicides have transformed agricultural weed control, greatly reducing human labor costs and increasing crop yields. However, there are significant ecological concerns associated with their widespread usage, especially for aquatic environments. With a focus on both direct and indirect paths of pollution and injury, this chapter examines the complex effects of herbicides on freshwater habitats. Through runoff, dispersion, leaching, spray deposition, herbicides enter aquatic systems and poison non-targeted creatures. Food webs and ecosystem processes are upset when aquatic flora, especially producers like algae primary and experience macrophytes, physiological stress, stunted development, and disturbed photosynthesis. Exposure to herbicides causes behavioral, developmental, and reproductive abnormalities in a variety of

fauna, including fish, amphibians, and macroinvertebrates. Because of their complicated life cycles and porous skin, amphibians are particularly vulnerable. Certain chemicals, such as glyphosate and atrazine. have been linked to developmental abnormalities and endocrine disruption. Aquatic food webs and human nutrition depend on fish populations, which are harmed by habitat degradation, bioaccumulation. physiological harm. When taken as a whole, these results demonstrate the widespread and enduring ecological effects of pesticide contamination in aquatic habitats. In order to reduce herbicide hazards and protect aquatic biodiversity, the chapter emphasizes the critical necessity for integrated management techniques and regulatory control.



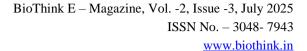


Introduction

Managing invasive plants has been a constant challenge since the dawn of agriculture by prehistoric beings. Due to this worry, people have developed various solutions, from using crude tools to applying lethal chemicals known "herbicides." Herbicides reduce laborintensive manual weeding and elevate the production and quality of cultivation. Herbicides have detrimental effects on the environment and human health, despite their effectiveness in eradicating weeds and undesirable plants. Because of their susceptibility to volatilization, leaching, and runoff, numerous herbicides may build up in soils, waterways, and tissue. These chemicals also have the potential to damage unexpected life forms (Mohd Ghazi et al., 2023). The term "Ghost in the water" signifies the unseen detrimental effects of herbicides in water bodies. Herbicides can alter food chains. change patterns of energy flow nutrient cycling, decrease variability in species and community frameworks, alter the health and endurance of ecosystems, and lower the sustainability of the environment once they are in aquatic ecosystems (Perez et al., 2011).

Herbicides frequently cause phytotoxicity to aquatic species that are not their intended target, like algae and macrophytes. These negative impacts on primary producers can ripple up the food chain, changing the composition of communities. All compounds with herbicidal mode of impact must undergo legal screening on primary producers that are not their target because herbicides explicitly target critical functions primary producers (Vonk & Kraak, 2020). Herbicides, which are intended to suppress undesirable plant development, can have a major impact on the growth, reproduction, and even survival of both specific and nontarget species of plants. Herbicides can upset plant biological systems, perhaps changing plant populations and affecting other creatures that rely on them, even if they are made to kill certain weeds (Boutin et al., 2014).

Although herbicides are good at keeping undesired plants under control, they may also have a direct negative impact on aquatic invertebrates via several processes,





such as decreased oxygen levels, changed water chemistry, and direct toxicity. Both invertebrate populations and the aquatic ecology may be negatively impacted by these consequences (Hasenbein *et al.*, 2017).

Herbicides have the potential to affect fish directly or indirectly. Indirectly, it affects fish by eliminating plants that are necessary for their natural environment or as sources of nutrition. Additionally, the oxygen may be dropped to levels that are not sufficient for fish to survive due to the biological oxygen requirement from the decomposing plants. Direct impacts on include alterations in behavior. reproductive potential, and physiological system abnormalities. Some herbicides can have long-lasting impacts on fish, although most are not acutely harmful because of their unique plant-targeting mechanisms. These impacts may affect fish survival and population dynamics and might vary from behavioral stress and changes to developmental and reproductive disturbances (Solomon et al., 2013).

This chapter aims to give a broad overview of the state of knowledge regarding

herbicides' direct and indirect impacts on the aquatic environment.

Conduits of Ecological Risk: How Herbicides Invade Water Bodies

Agricultural conduct is among the primary causes of herbicide pollution in aquatic environments; however, there are other and point sources as diffuse well. Herbicides can enter adjacent reservoirs through a variety of hydrological and atmospheric channels after being administered to terrestrial ecosystems, contaminating surface and groundwater and occasionally permanently widely (Carter, 2000). The most common routes of herbicides disposal in water bodies are:

1) Agricultural practices: The foremost source is drainage from agriculture. Excess herbicides that aren't taken up by crops or soils may be carried from fields into waterways during rainfall or irrigation events. Several variables, including soil type, herbicide composition, rainfall intensity, and application time, affect how much runoff occurs. Erosion is another way through which herbicides

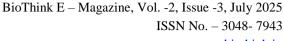


- attached to soil particles might get into aquatic systems.
- 2) Leaching/Percolation: Another significant route leaching, is for herbicides with especially limited soil absorption capacity and elevated affinity for water. These substances have the ability to pollute groundwater beneath the soil cover. Because groundwater pollution is persistent, has little natural attenuation, and takes an extended period to recover, it is especially worrying.
- drifts: 3) Chemical drift/Spray When applying herbicides, spray drift particularly happens, when aerial equipment is being used. Wind has the ability to carry droplets and lodge tiny them straight into nearby bodies of water. The danger of contamination from drift can be greatly increased by inappropriate spraying methods.
- 4) Chemical deposition from the atmosphere: An indirect but significant pathway is atmospheric deposition, which involves the dispersion of herbicides from the

treated areas and their further airborne transportation. Even at far-flung distances from their initial application locations, these compounds can subsequently be deposited into water bodies by precipitation or particle settling.

Effects of herbicides on aquatic flora

[1] **Non-Target Effects** and **Environmental Variables Influencing** Aquatic Plant Sensitivity: Herbicides affect the ecosystem's flora, which is not their intended target. Through disruptions to food web, nutrient cycling, and the health of water, utilization may also have indirect effects on the larger environment. All of aquatic species plants are susceptible to herbicides in water, whereas developing and floating ones can be exposed in the air, and rooted plants and benthic algae can be exposed in sediment. Herbicide dosage, interaction time, chemical characteristics (such as solubility and permanence), and the sensitiveness of certain plant species are some of the variables that affect the impact's magnitude. Acute exposure to large dosages can have an ecological impact, but

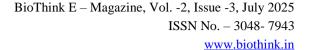






so can long-lasting exposure to minute quantities. Phytoplankton and free-living submerged plants in water are most vulnerable to soluble herbicides in water (Vonk & Kraak, 2020). Photosystem II inhibitors, including atrazine and bentazone. among the are several herbicides interfere that with These photosynthetic processes. substances impede the movement of electrons within chloroplasts, which results in decreased growth, hampered photosynthesis, and, in extreme situations, plant mortality. Additionally, physiological functions, including pigment production, respiration, nutrient absorption, can be interfered with by sub-lethal doses (Zhu et al., 2009).

[2] Functional Roles of Macrophytes and Consequences of Herbicide Herbicide **Interference:** exposure is especially dangerous for aquatic macrophytes, whose survival is essential to freshwater ecosystems. In addition to stabilizing sediments and producing oxygen, these plants provide crucial habitat for a variety of fish and invertebrate species. Herbicide exposure may cause more resistant macrophyte species multiply while sensitive to macrophyte species may decrease, altering the makeup of communities and upsetting the ecosystem's general structure and functionality (Chander et al., Contact herbicides have the potential to harm cell membranes or prevent certain enzymes that are essential for development and growth. Macrophytes may be directly or indirectly impacted by herbicides. Disruption of photosynthetic reactions, decreased development rates, injury to cells, and even plant death are examples of direct consequences. For instance, systemic herbicides like glyphosate can cause physiological stress by interfering with amino acid synthesis and being absorbed and transported throughout the The 5-enolpyruvyl-shikimate-3plant. phosphate synthase (EPSPS) enzyme is inhibited by glyphosate-based herbicides, which damage the shikimate pathway and frequently kill plants (Freitas-Silva et al., 2022). Atrazine is often found in aquatic habitats and has been shown to influence aquatic plant and animal reproduction, which in turn affects the general framework of the ecosystem.





Impacts of herbicides on aquatic fauna

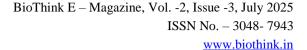
Despite their intended use against foreign weeds, herbicides can have unexpected effects on aquatic life because of their durability and prevalence in freshwater environments. Fish, amphibians, macroinvertebrates, and zooplankton are among the aquatic creatures prone to herbicides by direct contact with polluted waters, consumption of polluted food, or uptake through gill membranes. Numerous aquatic creatures may experience diminished growth and reproduction, behavioral and physiological abnormalities, and even death as a result of herbicide exposure.

Based on the species and phase development, herbicides have a wide range of adverse impacts on aquatic life. Herbicide poisoning can cause numerous kinds of physiological and developmental problems in fish and amphibians, including hormone imbalances, decreased for reproduction, impaired development, and increased death rates. As endocrine inhibitors, several herbicides interfere with the control of reproductive hormones and change the course of normal

reproductive growth. Even modest, non-lethal concentrations have the potential to have long-term effects on the population, making early life stages—especially larvae and juveniles—particularly sensitive.

With their critical roles in nutrient cycling and as a major source of nutrition for upper-trophic levels. aquatic macroinvertebrates are essential to the composition and operation of freshwater ecosystems. Even at low doses, herbicides can have a detrimental effect on the eating habits, mobility, respiration, and general survival of multiple macroinvertebrate species. A decrease in the variety richness of macroinvertebrates is commonly employed as a bioindicator of declining water quality, which usually indicates widespread ecological damage (Rumschlag et al., 2020). In this section, we will study the harmful effects of herbicides on various aquatic species.

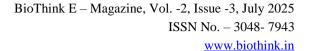
[1] **Hebicides** effects on macroinvertebrates: In aquatic environments, herbicides can have a detrimental effect on macroinvertebrate populations, reducing their variety, leading distribution, and even to





malformations. According to a study assessing the cumulative impact herbicides and insecticides on aquatic ecosystems, streams with higher herbicide concentrations had lower overall biomass shares of Trichoptera and Ephemeroptera relative to streams with lower herbicide concentrations. This demonstrates how the cumulative impacts of food-mediated herbicides on the biomass of vulnerable insect species upset food networks at the ecological level (Liebmann et al., 2024). bentazone concentrations were When applied plankton and benthic to ecosystems, the most impacted group concerning community structure plankton. With indirect impacts leading to the displacement of big filter feeders by tiny filter feeders, zooplankton was the subsequent most impacted group. This indicates that the herbicide had significant bottom-up impacts, changing the community pattern of primary producers, which subsequently had an indirect impact on important zooplankton species (Grillo-Avila et al., 2025). Hence, from these studies, we conclude that herbicides have harmful effects on aquatic macroinvertebrate fauna.

[2] Impacts on amphibians: Herbicides can enter the bodies of amphibians via their skin, gills, or by consuming tainted food or water. Excessive levels might result in serious destruction of tissues or instant death. Behavior, development, and physiology can all be impacted by even minute doses. For instance, Skin damage and respiratory problems, decreased body mass and delayed growth, altered swimming and foraging behavior can be observed. Glyphosate and atrazine, two researched herbicides. often demonstrated notable sublethal toxicity in a variety of frog species. Herbicides containing glyphosate, such as Roundup, have the potential to kill a lot of amphibian larvae. According to one study, Roundup killed 96–100% of the larval amphibians after three weeks of exposure (Relyea, 2005). Glyphosate's disruption of normal development and growth represents one of its prominent effects. In both larval and juvenile amphibians, exposure to even trace amounts can slow down development postponing metamorphosis lowering body size, which may have an subsequent survival impact on and reproduction. Additionally linked to



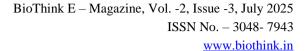


teratogenic effects, glyphosate can result in developmental defects in early life, including limb malformations and craniofacial anomalies. Glyphosate can physiological cause major system disruptions in addition to physical abnormalities. According to certain research. disrupts metabolic reproductive systems, resulting in changed hormone levels, decreased fertility, and aberrant gonad development (Paetow et al., 2023).

Being a well-known endocrine disruptor, atrazine, one of the most commonly used herbicides worldwide, may have an impact on the hormonal systems that control amphibian developmental processes and reproduction. The feminization of male frogs is among the most concerning consequences of atrazine exposure. Studies have revealed that it can result in intersex, a condition in which males produce both testes and ovaries, and in certain instances, it can lead to total chemical castration. This happens when testosterone levels are drastically lowered, which hinders the of development characteristics and behaviors unique to males that are for effective reproduction. necessary

Alongside these reproductive disturbances, atrazine can also affect juveniles' normal gonadal development, which further skews sex ratios and lowers reproductive fitness in wild populations (Hayes *et al.*, 2006). Hence, from these studies, one can find harmful effects of herbicides on developmental and reproductive pathways in amphibians.

[3] Effects on fish: As important moderators within food webs, fish play an essential role in aquatic environments by regulating the populations of different and preserving ecological creatures equilibrium. Apart from their biological relevance. fish also useful are bioindicators of the health of the environment. Fish populations' existence and condition can indicate the presence of contaminants like herbicides and provide insight into the general health of aquatic ecosystems, since they are susceptible to fluctuations in water quality and chemical pollution. Fish have a vital part in human society in addition to their function in the environment. They assist both food security and economic lives by serving as a significant source of protein and vital nutrients for people worldwide. Herbicides



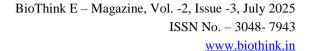


can harm fish by directly harming them, lowering their food supplies, and upsetting their environment. Fish are essential to aquatic systems and human food chains. Additionally, herbicides can build up in fish tissues, resulting in chronic health issues (Solomon, 2013; Travers-Trolet *et al.*, 2025).

At high quantities, herbicides—even those deemed to be relatively low in toxicity can be detrimental to fish, impairing their ability to survive, develop, and reproduce. By destroying plants that offer vital food and shelter, they can upset aquatic ecosystems, resulting in habitat loss and anomalies in the food chain. Herbicides can affect fish habits, development, and reproductive success even at sublethal concentrations. Over time, some substances may build up in fish tissues, which might endanger human consumers and result in long-term health problems. Herbicides have also been demonstrated to affect such survival-related behaviors as mating, predator prevention, and foraging. They may also occasionally result in histopathological harm to essential organs such as the kidneys, liver, and gills, which would further jeopardize the health and population stability of fish (Yang *et al.*, 2021; Lopes *et al.*, 2022; Ribeiro *et al.*, 2022).

Integrated Strategies for Controlling Herbicide Runoff

It takes a mix of sustainable methods, regulatory actions. and ecological rehabilitation to lessen the negative effects of herbicides on aquatic habitats. Adopting Best Management Practices (BMPs) in agriculture, such as integrated weed control, precision application, appropriate scheduling to minimize runoff, is one of the key tactics. Creating riparian vegetation and buffer zones aids in filtering pollutants before they enter water bodies. Herbicides are broken down by plants and bacteria in phytoremediation and artificial wetlands, which also act as natural filters. Better herbicide solutions, including compostable targeted or chemicals. can lessen toxicity longevity in the environment. Controlling herbicide contamination requires stricter laws that include concentration limits. environmental risk assessments, and monitoring. Sustainable periodic alternatives and appropriate use may be





encouraged through public education. Finally, continuous monitoring and research are essential for comprehending long-term impacts and directing adaptive management initiatives. When combined, these strategies support the preservation of aquatic plants, animals, and the general health of the environment.

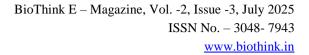
Research Gaps and Future Outlook

Comprehensive evaluations of newly developed herbicides and their prolonged, effects under ecologically persistent relevant settings should be the top priority forthcoming studies on herbicide poisoning in aquatic flora and animals. Understanding the ecological dangers of herbicide combinations will be enhanced by looking into the cumulative impact, along with the molecular and biochemical that underlie toxicity. processes Furthermore, research ought to concentrate on how herbicides influence ecosystem services and processes, including food web stability and nutrient cycling. Creating safer pesticide substitutes and enhancing assessment models through the integration of ecological and hydrological data are urgent priorities. It is also crucial

to take into account how climate change affects the toxicity and behavior of herbicides. Last but not least. standardizing testing procedures for various aquatic environments would improve data comparability and facilitate improved environmental management.

Conclusion

Despite being essential for agricultural herbicides continue to pose output, problems for aquatic ecosystem health. Ecosystem services, biodiversity, ecological balance can all be negatively impacted by their toxicity to aquatic plants and animals. The intricacy of these effects, which are regulated by variables including exposure time, chemical combinations, environmental circumstances, and highlighted by current research. We must improve our knowledge of the short- and long-term impacts of herbicides and use this information to environmental management and policy to protect aquatic life. Reducing damage and maintaining the sustainability of aquatic habitats will need ongoing innovation in safer pesticide formulations and enhanced risk assessment methodologies.





References

Mohd Ghazi, R., Nik Yusoff, N. R., Abdul Halim, N. S., Wahab, I. R. A., Ab Latif, N., Hasmoni, S. H., Ahmad Zaini, M. A., & Zakaria, Z. A. (2023). Health effects of herbicides and its current removal strategies. *Bioengineered*, 14(1), 2259526. https://doi.org/10.1080/21655979.2023.2259526.

Perez, G. L., Vera, M. S., & Miranda, L.
A. (2011). Effects of Herbicide
Glyphosate and GlyphosateBased Formulations on
Aquatic Ecosystems.
10.5772/12877.

Vonk, J.A. & Kraak, M.H.S. (2020).

Herbicide Exposure and
Toxicity to Aquatic Primary
Producers. In: de Voogt, P.
(eds) Reviews of
Environmental Contamination
and Toxicology Volume 250.
Reviews of Environmental
Contamination and
Toxicology, vol 250. Springer,

Cham.

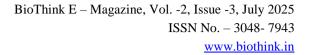
https://doi.org/10.1007/398_20 20_48.

Boutin, C., Strandberg, B., Carpenter, D., Mathiassen, S. K., & Thomas, P. J. (2014). Herbicide impact on non-target plant reproduction: what are the toxicological and ecological implications?. *Environmental Pollution*, 185, 295-306.

Hasenbein, S., Lawler, S. P. & Connon, R. E. (2017). An assessment of direct and indirect effects of two herbicides on aquatic communities, *Environmental Toxicology and Chemistry*, 36(8), 2234–2244. https://doi.org/10.1002/e tc.3740.

Solomon, K. R., Dalhoff, K., Volz, D., & Van Der Kraak, G. (2013). Effects of herbicides on fish. In *Fish physiology* (Vol. 33, pp. 369-409). Academic Press.

Carpenter, D. J., Mathiassen, S. K., Strandberg, B.B., Casey, C. S.





& Damgaard, C. (2020). Effects of Herbicides on Flowering, *Environmental Toxicology and Chemistry*, 39(6), 1244–1256. https://doi.org/10.1002/e tc.4712.

Carter, (2000). Herbicide movement in soils: Principles, pathways and processes. *Weed Research*, 40, 113 - 122. 10.1046/j.1365-3180.2000.00157.x.

Vonk, J.A. & Kraak, M.H.S. (2020). Herbicide **Exposure** and Toxicity to Aquatic Primary Producers. In: de Voogt, P. Reviews (eds) of Environmental Contamination and Toxicology Volume 250. Reviews of Environmental Contamination and Toxicology, vol 250. Springer, Cham. https://doi.org/1.1007/398_202

Zhu, J., Patzoldt, W. L., Radwan, O.,
Tranel, P. J., & Clough, S. J.
(2009). Effects of

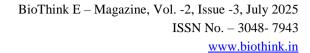
0 48.

photosystem-II-interfering herbicides atrazine and bentazon on the soybean transcriptome. *The Plant Genome*, 2(2). https://doi.org/10.3835/plantge nome2009.02.0010.

Chander, S., Gujrati, A., Krishna, A. V.,
Sahay, A., & Singh, R. P.
(2020). Remote sensing of
inland water quality: A
hyperspectral perspective.
In *Hyperspectral Remote*Sensing (pp. 197-219).
Elsevier.

Freitas-Silva, L. D., Araújo, H. H., Meireles, C. S., & Silva, L. C. D. (2022). Plant exposure to glyphosate-based herbicides and how this might alter plant physiological and structural processes. *Botany*, 100(6), 473-480. https://doi.org/10.1139/cj

Rumschlag, S. L., Mahon, M. B.,
Hoverman, J. T., Raffel, T. R.,
Carrick, H. J., Hudson, P. J., &





Rohr, J. R. (2020). Consistent effects of pesticides on community structure and ecosystem function in freshwater systems. Nature communications, 11(1), 6333. https://doi.org/10.1038/s41467 -020-20192-2.

Liebmann, L., Schreiner, V. C., Vormeier, P., Weisner, O., & Liess, M. (2024). Combined effects of herbicides and insecticides reduce biomass of sensitive aquatic invertebrates. Science of the Total Environment, 946, 174343.Liebmann. L., Schreiner, V. C., Vormeier, P., Weisner, O., & Liess, M. (2024). Combined effects of herbicides and insecticides reduce biomass of sensitive aquatic invertebrates. Science of the Total Environment, 946, 174343.

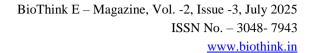
Grillo-Avila, D., Anton-Pardo, M.,
Armengol, J., Puche, E.,
Carballeira, R., MoratallaLopez, J., Palacios-Abella,

J.F., López, I., Crettaz Minaglia, M.C., Amador, P. & Rochera, C. (2025). Effects of the herbicide bentazone on the of plankton structure benthic communities representative of Mediterranean coastal wetlands: a mesocosm experiment. Hydrobiologia, 85 2(10),2709-2728. https://doi.org/10.1007/s10750 -024-05779-w.

Relyea, R. A. (2005). The lethal impact of
Roundup on aquatic and
terrestrial
amphibians. *Ecological*applications, 15(4), 11181124.
https://doi.org/10.1890/04-1291.

Paetow, L. J., Cue, R. I., Pauli, B. D., &
Marcogliese, D. J. (2023).

Effects of herbicides and the
chytrid fungus
Batrachochytrium
dendrobatidis on the growth,
development and survival of





larval American toads (Anaxyrus americanus). *Ecotoxicology and Environmental Safety*, 259, 115021. https://doi.org/10.1016/j.ecoen v.2023.115021.

Hayes, T. B., Stuart, A. A., Mendoza, M., Collins, A., Noriega, Vonk, A., Johnston, G., Liu, R., & Kpodzo, D. (2006). Characterization of atrazineinduced gonadal in malformations African clawed frogs (Xenopus laevis) and comparisons with effects of an androgen antagonist (cyproterone acetate) exogenous estrogen (17betaestradiol): Support for the demasculinization/feminizatio hypothesis. Environmental health perspectives, 114 Suppl 134-141. 1(Suppl 1), https://doi.org/10.1289/ehp.80 67.

Solomon, K. R., Dalhoff, K., Volz, D., & Van Der Kraak, G. (2013).

Effects of herbicides on fish. In *Fish physiology* (Vol. 33, pp. 369-409). academic press. https://doi.org/10.1016/B978-0-12-398254-4.00007-8.

Travers-Trolet, M., van Denderen, P. D.,
Deniau, C., Gascuel, D.,
Lobry, J., & Trueman, C.
(2025). The role of fish in
marine food webs. In *Ecology*of Marine Fish (pp. 257-266).
Academic Press.
https://doi.org/10.1016/B978-0-323-99036-3.00013-1.

Yang, C., Lim, W., & Song, G. (2021).

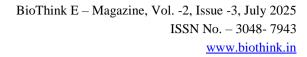
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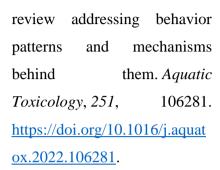
Biochemistry and Physiology

Part C: Toxicology & Pharmacology, 248, 109103.

https://doi.org/10.1016/j.cbpc.
2021.109103.

Lopes, A. R., Moraes, J. S., & Martins, C. D. M. G. (2022). Effects of the herbicide glyphosate on fish from embryos to adults: a





Ribeiro, Y.M., Moreira, D.P., Weber,
A.A., Sales, C.F., Melo,
R.M.C., Bazzoli, N., Rizzo, E.

& Paschoalini, A.L. (2022). Adverse effects of herbicides in freshwater Neotropical fish: A review. *Aquatic Toxicology*, 252, p.106293. https://doi.org/10.1016/j.aquatox.2022.106293.