

Glyphosate Sustainability: Evaluating the Environmental and Human Health Trade-Offs of Glyphosate Use in Agriculture

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Abstract—Glyphosate, the most extensively utilized herbicide globally, has transformed contemporary agriculture due to its efficacy in weed management and its suitability for conservation tillage practices. The integration with genetically modified herbicide-tolerant (HT) crops has enhanced productivity, diminished labor, and decreased expenses. Nonetheless, heightened scrutiny has arisen concerning glyphosate's environmental durability and possible health effects. This paper rigorously assesses the sustainability of glyphosate utilization by analyzing its environmental impacts on soil integrity, water quality, and biodiversity, alongside its potential associations with cancer, endocrine disruption, and other chronic health conditions in humans. Glyphosate provides economic advantages via enhanced yields and diminished inputs; however, these benefits are counterbalanced by ecological deterioration, the emergence of resistant weeds, and expensive legal disputes. The research compares glyphosate-based systems with organic and integrated weed management (IWM) methods, emphasizing alternative strategies that sustain productivity while reducing health and environmental hazards. The paper presents evidence-based policy recommendations derived from scientific literature, institutional reports, and regulatory reviews, encompassing stakeholder engagement, monitoring systems, labeling transparency, and financial incentives for sustainable practices. Ultimately, it underscores the necessity for a balanced, adaptive strategy that navigates the intricate trade-offs related to glyphosate to guarantee enduring agricultural sustainability and public health.

Index Terms—Glyphosate, sustainability, agriculture, environmental impact, integrated weed management (IWM), health effects.

1. INTRODUCTION

Glyphosate has played an essential role in modern agricultural systems, particularly since the

introduction of glyphosate-tolerant genetically modified (GM) crops in the 1990s, and is renowned for its effectiveness in controlling a broad spectrum of weeds(1). It is the most widely used herbicide worldwide. Not only is it inexpensive and compatible with conservation tillage, which helps decrease fuel use and soil erosion, but it also acts non-selectively, which contributes to its popularity(2). However, glyphosate's heavy use is coming under more and more scrutiny as a result of human and environmental health concerns. Much research has focused on the environmental fate of glyphosate, including its effects on non-target creatures, the soil microbial communities it disrupts, and its role in weed resistance(3). The possible health risks, such as cancer, endocrine disruption, and chronic toxicity, continue to be a topic of debate, with researchers and regulatory agencies coming to different conclusions. Complexities like these underscore a major obstacle to sustainable agriculture: finding a happy medium between glyphosate's productivity gains and its negative effects on health and the environment(4)(5). Policymakers, farmers, and consumers must assess this equilibrium if they want food systems that can withstand and adapt to a changing world.

2. OBJECTIVE

This paper aims to analyze the trade-offs between the agricultural benefits and the associated environmental and human health risks of glyphosate in order to critically evaluate the sustainability of its use in agriculture. The focus of this study is to

- Examine the environmental consequences of glyphosate application, focusing on its effects on soil health, water quality, and biodiversity.
- Investigate the potential human health implications tied to glyphosate exposure,

including associations with cancer, neurological disorders, and other chronic health conditions.

- Assess the economic advantages glyphosate offers to agricultural productivity and efficiency, and weigh these against the environmental and health-related costs.
- Identify and evaluate alternative weed management strategies capable of reducing glyphosate dependency without compromising crop yields or farm profitability.
- Develop actionable policy recommendations and decision frameworks to help policymakers and stakeholders balance glyphosate's benefits and risks for sustainable agricultural development.

3. METHODOLOGY

This study utilizes a Qualitative research methodology, integrating data from established peer-reviewed articles, reviews, institutional reports, regulatory documents, and meta-analyses regarding glyphosate's environmental, health, and economic effects. Principal sources encompass scientific databases (e.g., PubMed, ScienceDirect), reports from organizations such as the WHO and EPA, and international regulatory declarations. A comparative analysis is performed on findings pertaining to soil health, water quality, biodiversity, human health risks, economic outcomes, and policy.

4. DISCUSSION

1. Understanding Glyphosate

Glyphosate is a broad-spectrum herbicide that is an essential tool in contemporary agriculture due to its efficacy and distinct mechanism. Its main mechanism of action involves inhibiting 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), an enzyme that is a crucial catalyst in the shikimate pathway, which is in charge of the biosynthesis of the essential aromatic amino acids tryptophan, phenylalanine, and tyrosine in plants(6). Applying glyphosate causes it to be absorbed through the foliage and move throughout the plant, eventually reaching tissues like roots and shoots that are actively growing(7). The accumulation of shikimate, a crucial biomarker for differentiating between glyphosate-sensitive and -resistant plants, occurs when the

synthesis of these amino acids is disrupted by EPSPS inhibition. Since these amino acids are necessary for the synthesis of proteins, this blockage ultimately results in plant death(8).

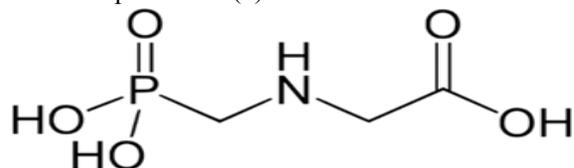


Fig 1:- Structural formula of glyphosate

Glyphosate is very effective against plants and reasonably safe for mammals at normal exposure levels because it doesn't affect the shikimate pathway in animals, which contributes to its specificity. Glyphosate is commonly used in agriculture for pre-plant weed control, non-selective management in non-crop areas, and—most importantly—post-emergence spraying in genetically modified glyphosate-resistant crops like cotton, soybean, and maize that can withstand the herbicide because of specially engineered or introduced EPSPS genes(9). The frequent and heavy application of glyphosate, however, has caused resistance to develop in weed populations via a number of mechanisms. Certain weeds acquire target-site resistance through EPSPS gene mutations, which change the binding site and prevent glyphosate from efficiently blocking enzyme activity(10). In *Amaranthus* species, for instance, triple mutations in EPSPS have been found, resulting in high resistance. EPSPS gene amplification is another common mechanism, in which weeds produce enough of the enzyme to overcome glyphosate inhibition by carrying extra copies of the target gene(11)(12). Non-target-site resistance, which avoids the herbicide from reaching its site of action, can include decreased glyphosate translocation within the plant or quick sequestration into vacuoles. In order to increase their resistance, certain plants may combine non-target-site and target-site mechanisms. In light of these resistance issues, integrated weed control methods are crucial(13). Herbicides with different modes of action can be rotated, pre-emergence herbicides like diuron and sulfentrazone can be used, and mechanical or cultural control methods can be used to lessen selection pressure and weed seed banks(14). Compliance and monitoring are aided by developments in molecular detection, such as the chromatographic detection of shikimate, which

distinguishes between crops that are susceptible to glyphosate and those that are.

2. Environmental Impacts of Glyphosate Use

a. Soil Health

The widespread application of glyphosate in agricultural settings raises serious concerns about the state of soil health, as mounting evidence points to negative impacts on soil chemistry, microbial dynamics, and ecological functions. Glyphosate, a systemic herbicide that does not selectively target any one organism, disrupts the synthesis of essential amino acids by targeting the enzyme EPSPS in both plants and microbes. Although this mechanism is efficient at controlling weeds, it has unintended consequences for soil organisms and communities of microbes that are vital to soil health(15). Soil fertility decreases and ecological processes are impaired as a result of long-term glyphosate use, which disrupts soil microbial biomass and composition. In the case of coffee cultivation, for instance, field observations showed that glyphosate-treated plots had substantially lower pH levels and organic matter content than untreated plots(16). Reduced organic matter and acidity lead to fewer microbes and slower herbicide residue breakdown, which in turn reduces soil resilience and further complicates farm management. Also, studies show that after being exposed to glyphosate, soil microbial communities can change, which can lead to the suppression of good microbes like rhizobacteria, which promote plant growth, and the increase of bad molds and bacteria. Plants may become more vulnerable to soil-borne diseases, such as *Fusarium* and *Rhizoctonia*, as a result of these disturbances, which undermine nutrient cycling, soil stability, and their inherent resistance to such diseases(17). Overarchingly, concerns regarding the persistence and movement of glyphosate and its metabolite AMPA through ecosystems are raised by the detection of elevated levels of these compounds in agricultural soils, which have been discovered in various environments. Soil microbes are mainly responsible for glyphosate degradation, but its residues and degradation products are becoming more common as usage increases, which could mean accumulation and long-term contamination risks(18). Applying biochar amendments can alter the soil's reaction to pesticide inputs, which in turn reduces the detrimental impacts of glyphosate on soil health. Further research is

necessary to determine the long-term effectiveness of using biochar as a mitigation strategy for glyphosate, but preliminary findings suggest that it can mitigate some of the pesticide's negative effects on microbial biomass by acting as a chemical sink and creating an ideal environment for soil organisms(19).

b. Water Quality

Water quality is greatly impacted by the widespread use of glyphosate in agriculture. This chemical affects both surface and groundwater systems in various agricultural regions. Surface runoff, leaching, and drift are all ways that glyphosate, which is both very soluble and relatively stable in many environments, can end up in bodies of water after or during application. The long-term viability of farming methods and the safety of water supplies for people and the environment are both jeopardized by the subsequent pollution. As a quantitative measure of the impact of agricultural emissions on water systems, the "water quality footprint" has recently been proposed in large-scale studies. These emissions include glyphosate, nitrogen, and phosphorus. How much potable water is required to dilute contaminants to an acceptable level is determined using this method. Imported crops in Germany's bioeconomy have left a massive "virtual water quality footprint" due to the presence of glyphosate and other agrochemical residues. Actually, if Germany wanted to reduce the pollution from its agricultural imports by diluting them all, it would need a lot more water than is actually used to irrigate these crops. This disparity can be as large as 300 times greater than what is available in important exporting regions like India, China, and Spain. This discovery stresses the necessity for more stringent worldwide management of pesticide emissions and shows how glyphosate emissions contribute to water scarcity around the world. It also calls into question the long-term viability of agricultural supply chains that are heavily reliant on exports(20).

Scientific investigations into water bodies and catchments have proven that glyphosate residues are present and persist in sediments and water. Results from field investigations utilizing high-performance liquid chromatography (HPLC) show that glyphosate accumulates in aquatic organisms and is present in river water at concentrations ranging from 1.26 to 1.65 µg/L and in sediments at concentrations ranging from 0.06 to 0.23 mg/kg. For example, glyphosate

and its byproducts were found in detectable amounts in the liver, gills, and muscle tissue of fish sampled from the Sassandra River in Côte d'Ivoire. Children under the age of 18 showed bioaccumulation of these contaminants from fish consumption, which raises long-term ecological and public health concerns, particularly with chronic exposure. The resultant hazard quotients did not indicate any substantial immediate health risks for adults, though. Glyphosate can enter food chains and accumulate in aquatic organisms, which could have consequences for ecosystem health and higher trophic levels(21).

Agricultural management practices, weather, and soil type all impact glyphosate's environmental behavior. Despite glyphosate's lower mobility compared to more persistent herbicides due to its strong affinity for soil particles, it can still migrate to groundwater under specific conditions. Groundwater can contain detectable levels of glyphosate, despite its typically low concentrations, due to processes like preferential flow that speed up the vertical movement of the herbicide through the soil profile, particularly after periods of heavy rainfall. In areas where application rates are high and precipitation follows application events, lysimeter studies show that shallower groundwater and surface runoff can still have problematic concentrations of glyphosate and similar herbicides, even though these substances are not usually transported to deep groundwater at levels that cause acute environmental concerns(22).

Glyphosate contamination in water systems has ecological implications that go beyond its direct toxicity. Many aquatic creatures, such as fish, amphibians, macroinvertebrates, and plants, are susceptible to changes in their physiology, behavior, and ability to reproduce when exposed to levels below the lethal threshold. All levels of aquatic life are at risk because glyphosate and its metabolite AMPA cause oxidative stress and interfere with enzyme activities. Subtle but substantial changes in the composition of aquatic communities have been linked to long-term low-level exposure, including the extinction of sensitive species, the expansion of tolerant taxa, and the suppression of primary productivity(23). These alterations have the potential to change nutrient cycling, undermine ecosystem services, and make bodies of water less resistant to other stresses. The possibility of human exposure through recreational contact and drinking water is

also included in risk assessments. Although glyphosate maximum contaminant levels (MCLs) have been set in many areas, increased water quality monitoring has been necessitated due to contamination "hotspots" in agricultural watersheds. A growing body of evidence indicates that surface and groundwater, including treated municipal water supplies in certain regions, can contain persistent levels of glyphosate, putting regulatory frameworks under increasing pressure to change. The significance of reducing waterborne glyphosate whenever feasible is highlighted by the ongoing debates surrounding chronic health effects and potential carcinogenicity, even though acute toxicity in humans at environmental exposure levels seems to be limited. Nitrogen and phosphorus fertilizers, for example, often co-occur and can worsen eutrophication, algal blooms, and hypoxic conditions; glyphosate's effects on water quality must be evaluated in conjunction with these synergistic interactions. To safeguard water quality at catchment and watershed scales, it is essential to employ integrated strategies that incorporate reduced chemical inputs, improved land management, buffer strips, restoration of wetlands, and precision agriculture, in addition to glyphosate use management.

c. Biodiversity

Glyphosate's widespread use in commercial agriculture around the world has made its effects on biodiversity a key topic of discussion in environmental and public health circles. In many ecosystems, this herbicide—one of the most widely used chemical weed control products—is linked to a decrease in biological diversity. Glyphosate use has been shown in recent decades to have the potential to directly and indirectly affect aquatic and terrestrial biodiversity. In agricultural landscapes, glyphosate can also harm non-target plants, such as those at field edges and in natural habitats next to cultivated areas, in addition to targeting undesirable weeds. Ecological networks are impacted by the loss of food and habitat resources caused by the decline of glyphosate-sensitive species, which reduces plant diversity. Insects, birds, and other wildlife that depend on a variety of plants for survival suffer as a result(24).

The effects of glyphosate in aquatic ecosystems are strongly related to rain, catchment features, field

locations, and agricultural practices, all of which influence the herbicide's entry into water bodies. After being released, glyphosate and its byproducts have the potential to linger and upset the delicate equilibrium of freshwater ecosystems. The quick biodegradation of glyphosate, which is frequently seen as a good thing, actually releases phosphorus into aquatic environments, according to recent studies(25). This may cause water bodies to become more eutrophic, which would promote the mass growth of some organisms like metaphyton and picocyanobacteria while decreasing the relative abundance and diversity of other taxa. In impacted freshwater habitats, these ecosystem shifts result in decreased oxygen, more algal blooms, and ultimately less biodiversity. They also change the structure and operation of aquatic systems. A dose-dependent increase in mortality among sensitive invertebrate species has also been demonstrated by experimental studies using herbicides based on glyphosate.

Studies employing the fruit fly model organism, *Drosophila melanogaster*, have revealed that higher concentrations of glyphosate result in noticeably higher lethality. This finding raises questions regarding possible hazards to other invertebrate populations that are frequently exposed to glyphosate in the environment(26). The survival and food consumption of honeybees, an important pollinator group, are negatively impacted by exposure as well, indicating wider implications for pollinator populations and the crucial ecosystem services they sustain. Both the direct toxicity to non-target organisms and the more intricate and systemic effects of glyphosate on ecosystems are documented in the expanding body of scientific literature. These include changes in important ecological processes like nutrient cycling as well as modifications to the structure of communities(27). Importantly, glyphosate's effects on the environment depend on local ecological context and application methods; regions with high agricultural activity and poor buffer management are likely to suffer the greatest losses in biodiversity. As more research is conducted, it becomes more evident that glyphosate has substantial and varied effects on biodiversity, which emphasizes the urgent need for integrated weed control and stronger environmental protections in agricultural practices.

3. Human Health Effects

a. Cancer and Chronic Disease Links

The International Agency for Research on Cancer (IARC) designated glyphosate-based herbicides (GBHs) as "probably carcinogenic to humans" in 2015. This designation has raised serious concerns about the possible connections between glyphosate exposure and the onset of cancer and other chronic diseases. New and compelling information on this topic has been made available by recent extensive toxicological studies, such as the Ramazzini Institute's Global Glyphosate Study (GGS). Glyphosate and two commercial GBH formulations were routinely administered to male and female rats in the GGS at doses that mirrored those that humans might encounter in the environment, including doses equal to the EU's permissible daily intake and the level at which no adverse effects were observed. In several organ systems, the incidence of both benign and malignant tumors increased in a dose-related manner that was statistically significant. These comprised cancers that developed in the skin, liver, thyroid gland, nervous system, ovary, mammary gland, adrenal glands, kidneys, bladder, bone, and the haemolymphoreticular system (leukemia), among other tissues. Notably, a large number of these tumors were uncommon in the strain of rats that were used, and some cancers, like leukemia, showed up earlier in life and were associated with higher early mortality in animals that were exposed(28).

The results of this animal study are in line with some human epidemiological research that revealed links between occupational glyphosate exposure and increased risks of developing some cancers, especially non-Hodgkin lymphoma. These findings support the IARC's conclusion and point to the biological plausibility of carcinogenic effects, particularly at doses comparable to those designated "safe" by regulatory bodies and in early life. The scientific debate is still going strong, though, as several regulatory bodies have revised or removed restrictions on glyphosate use after concluding that the chemical does not pose a significant risk of cancer at currently allowed exposure levels after reviewing industry and academic studies. The general public's exposures have also been found to be below safety thresholds in the majority of population-based studies employing biomonitoring; recent data even suggests declining exposure trends since

2020(29). Thus, many regulatory risk assessments consider the overall risk to the general population to be low, even though there is strong experimental and some epidemiological evidence for carcinogenic potential, particularly at higher or chronic exposures. Beyond cancer, research is still being done on potential connections between glyphosate and chronic diseases like neurological disorders, metabolic dysfunction, and endocrine disruption. Through processes like oxidative stress, hormone disruption, or microbiome alteration, glyphosate may contribute to the etiology of diseases other than cancer, according to certain laboratory and epidemiological research. However, more thorough, long-term research is needed to completely understand these pathways and their practical implications for public health. In conclusion, current research shows that glyphosate is carcinogenic in animal studies and that it has biological plausibility for human cancer risk, especially for some cancer types that are associated with high levels of chronic or occupational exposure(30). The need for ongoing monitoring and independent research is further supported by the overwhelming body of evidence from population biomonitoring and regulations that suggests risks to the general public under current usage conditions are still up for scientific debate.

b. Comparison with Organic Practices

There are notable differences in the effects of conventional agriculture, which uses glyphosate, and organic farming methods on human health, crop productivity, and the environment. Crop rotation, mechanical weeding, biological pest control, and the use of farmyard and green manures to manage soils and pests are all preferred in organic farming, which forbids the use of synthetic chemical herbicides like glyphosate. Organic systems can therefore significantly increase the amount of soil organic carbon (SOC), encourage higher levels of soil microbial biomass, and improve the composition and diversity of soil microbial communities. In contrast to deep conventional tillage, which typically results in stable or slowly declining SOC levels, recent long-term studies show that switching from conventional to organic management, particularly with conservation tillage, results in significantly higher SOC concentrations—up to 43% greater in the upper soil layer over several years. In addition to reducing environmental degradation, this all-encompassing

improvement of soil health under organic systems promotes sustainable land productivity.

Impacts on health are yet another important comparison axis. Food produced using organic systems tends to have lower levels of biocides and synthetic pesticide residues, while having higher levels of antioxidants, phenols, and a more favorable fatty acid profile in animal products, according to reviews of the literature published since 2005. Studies on the feeding of humans and animals have occasionally revealed little to no differences in quantifiable health outcomes, but there are signs that eating organic food may reduce the risk of metabolic syndrome, allergies, obesity, and some types of cancer. Furthermore, microbial community composition in soils under organic regimes seems to be more favorable for beneficial plant-microbe interactions, even though total diversity indices do not always show significant differences. Compared to intensive chemical systems, organic plots have been found to harbor higher abundances of "probiotic" microbes that enhance plant growth and nitrogen availability, sometimes at the expense of overall yield or nutrient supply.

Problems with organic systems include higher weed pressure and labor intensity, which can lower yields compared to conventional systems—particularly when viable alternatives to weed control are not available—and this can have a negative impact on farmers' ability to make a living. Even though innovative management practices like split-applied manure and optimized land arrangements can boost productivity in double rice and organic wheat cropping systems, studies show that organic yields are typically lower. Although these systems may not produce as much per hectare, they are able to command higher prices on the market, which ensures their economic sustainability. Emerging as a solution to the disconnect between sustainability and productivity, integrated approaches like Integrated Nutrient Management (INM) integrate inorganic and organic inputs to improve soil properties, decrease emissions of greenhouse gases, and strike a balance between synthetic and natural interventions.

4. Economic Pros and Cons

Economic Benefits of Glyphosate Use

- Agricultural Productivity & Reduced Input Costs : The use of glyphosate in conjunction with GM herbicide tolerant (HT) crops has greatly

increased agricultural productivity and crop yields. A study conducted in 2017 estimated that glyphosate use and genetically modified (GM) hybrid (HT) cropping could increase global farm income by about USD 6.76 billion per year. The study also found that GM HT cropping could increase corn yield by 3.1 million tons, canola yield by 1.44 million tons, and soybean yield by 18.6 million tons. Furthermore, conventional crop failure without pesticides may result in yield reductions of approximately 10%, whereas wider pesticide use, including glyphosate, has been demonstrated to increase yields by 12-27% on average(31)(32).

- Lowering Labor, Fuel, and Equipment Costs via Conservation Tillage : Glyphosate is a great tool for no-till or reduced-tillage farming because it keeps weeds in check without disturbing the soil mechanically. Fewer crops mean less fuel use, fewer workers needed, and less machinery wear and tear. According to a literature review conducted in the European Union, glyphosate withdrawal would lead to an increase in intensive tillage practices, which in turn would increase production costs for wheat by 27–134 euros per hectare, or €690 million to €3.4 billion for crops grown in the EU. Further reduction of output value of between €1.6 and €7.1 billion occurs due to yield losses of 7 to 30 percent(33).
- Global Welfare and Food Price Stability : Global welfare losses totaling around USD 7.4 billion per year, primarily in key agricultural regions such as the U.S., South America, EU, and Brazil, would be induced by banning glyphosate, according to macroeconomic modeling. This ban even includes GM HT cropping. The food markets could experience inflationary pressure due to a potential 5.4% increase in global crop prices for staples like soybeans, along with smaller but significant price hikes for grains and oilseeds(31).
- Market Dominance & Scale Economies : Generic herbicides that do not contain glyphosate and alternative methods are typically more expensive than systems that do, particularly when applied in large quantities. Discount generic chemicals have become more popular among American farmers as a cost-cutting measure. However, these chemicals come with drawbacks like reduced

reliability and no warranty for recourse in the event of a failure. As a result, glyphosate is still a viable and efficient option for large producers.

Economic Drawbacks and Hidden Costs

- Environmental Externalities and Long-Term Soil Health : Glyphosate allows for reduced tillage, which saves soil and carbon, but removing it might mean going back to intensive tillage, which increases emissions of greenhouse gases, soil erosion, and decreasing fertility in the long run. If glyphosate becomes unavailable, farmers may abandon conservation agriculture practices, which would have negative effects on both the environment and financial stability.
- Litigation and Corporate Financial Liability : Glyphosate has been the subject of numerous lawsuits claiming that it causes harm to human health. Bayer, the main producer of glyphosate, has set aside tens of billions of dollars to pay out in lawsuits; the company has paid out more than \$9 billion in settlements alone, and the yearly litigation costs are reportedly as high as \$2 to \$3 billion, which cuts into the agribusiness profits from selling Roundup-like products. Even though these are the responsibility of the corporations involved, they have far-reaching consequences that might influence product prices, perceptions of regulatory risk, and R&D spending, all of which have the potential to influence farmers and consumers.
- Short-Term Transition Costs and Profit Margin Impacts : Glyphosate withdrawal may increase the costs of cultivation, fuel, labor, and capital expenditures for new systems or equipment. Vineyards in Europe can cost as much as €553 per hectare, according to farm research, and even relatively small crops, like maize, can lose €2–€3 per hectare each season. Particularly impacted by these cuts, which amount to 11%-11% of profit margins, are small and high-value crop systems.
- Food Price Inflation and Consumer Effects : Evidence reveals that if glyphosate usage is discontinued, food prices could rise and crop yields could fall. As an illustration, in the United Kingdom, it was anticipated that a prohibition would lead to a 70% decrease in wheat production, which in turn would increase consumer prices and jeopardize food security, as

well as a reduction in agricultural output of approximately £940 million annually, which is roughly £200 million in lost tax revenue(34).

Balancing Benefits and Costs: Trade-Offs

- **Immediate Gains vs Long-Term Sustainability :** Glyphosate has significant short-term monetary advantages, including increased efficiency, decreased fuel and labor costs, higher yields, and encouragement of conservation tillage. Nevertheless, the economic value could be diminished in the long run due to the risks associated with using just one chemical input, such as resistant weeds, ecological degradation, and legal exposure.
- **Economic Resilience & Innovation Imperative :** The agricultural sector is encountering systemic problems due to the maturation of generic pesticide markets and the rise in litigation risks. Bayer and other companies are threatening to stop producing glyphosate unless certain legal safeguards are put in place. They are referring to the crippling costs of litigation and the uncertain returns on herbicide innovation as their reasons. Investing in new crop protection technologies can be hindered by this uncertainty, which could limit future gains in sustainability and productivity.

5. Alternative Weed Management Strategies

- **Integrated Weed Management (IWM):** Combines chemical, mechanical, and cultural approaches to reduce herbicide dependence while maintaining productivity.
- **Organic Farming:** Relies on crop rotation, mechanical cultivation, cover cropping, and biological controls, promoting soil and ecosystem health.
- **Precision Agriculture:** Utilizes targeted application to minimize chemical inputs.
- **Biological Herbicides:** Exploration of natural weed control agents to replace or supplement glyphosate.

The use of organic and diversified methods has shown several advantages, including better soil health, less chemical residues, and increased biodiversity. Premium pricing can keep things economically viable, but there are some significant challenges, such as higher labor and production costs.(35)

6. Policy and Stakeholder Considerations

- **Evidence-Based Regulation:** Policymakers should base regulations on the latest independent scientific research regarding glyphosate's health and environmental impacts, frequently updating risk assessments as new data emerge.
- **Stakeholder Engagement:** Effective policies require active engagement with diverse stakeholders, including farmers, scientists, industry representatives, environmental groups, and consumers, ensuring their perspectives shape decision-making.
- **Integrated Weed Management Incentives:** Policies can promote adoption of alternative and integrated weed management strategies by offering financial incentives, research funding, training, and technical support.
- **Transparency and Labeling:** Clear labeling of glyphosate usage and residues in food products can empower consumer choice and enhance public trust.
- **Monitoring and Compliance:** Establishing robust systems for monitoring glyphosate residues and enforcing compliance is critical for both environmental protection and human health.
- **Global Coordination:** International collaboration is necessary to harmonize standards, track global trade implications, and prevent burdens from shifting across countries due to differing regulations.
- **Support for Transition:** Targeted support can assist farmers transitioning to more sustainable weed management systems, reducing potential economic disruptions.

5. CONCLUSION

The long-term viability of glyphosate use in farming depends on finding a happy medium between the herbicide's possible benefits to crops and the environment and people's health. It is indisputable that glyphosate has helped boost agricultural output, decrease fuel and labor inputs, and spread conservation tillage methods. There are limits to relying too heavily on this herbicide, though, due to rising worries about soil degradation, water contamination, biodiversity loss, and potential human health effects, particularly cancer and chronic diseases. According to research on the effects of

glyphosate on the environment, this herbicide has a negative impact on aquatic ecosystems, kills off pollinators, and harms non-target species. While regulatory bodies generally consider exposure levels safe, scientific data from studies on animals and humans reveals a potential association with carcinogenicity and endocrine disruption at levels encountered in the workplace or over an extended period of time. Glyphosate may work economically in the short term, but it has hidden liabilities in the long run due to issues like weed resistance, litigation costs, and environmental externalities. There must be a shift toward more diverse and integrated weed management approaches. Organic farming, precision agriculture, and Integrated Weed Management (IWM) are some of the methods that can help farmers increase yields with less chemical input. To ensure a sustainable transition, stakeholders, including scientists, policymakers, and farmers, must work together to develop adaptive regulatory frameworks based on independent scientific research and to provide farmers with financial, policy-driven, and technical resources.

REFERENCES

- [1] Duke SO, Powles SB. Glyphosate: a once-in-a-century herbicide. *Pest Manag Sci* [Internet]. 2008 Apr 13;64(4):319–25. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/ps.1518>
- [2] Cerdeira AL, Duke SO. The Current Status and Environmental Impacts of Glyphosate-Resistant Crops. *J Environ Qual* [Internet]. 2006 Sep;35(5):1633–58. Available from: <https://access.onlinelibrary.wiley.com/doi/10.2134/jeq2005.0378>
- [3] Myers JP, Antoniou MN, Blumberg B, Carroll L, Colborn T, Everett LG, et al. Concerns over use of glyphosate-based herbicides and risks associated with exposures: a consensus statement. *Environ Heal* [Internet]. 2016 Dec 17;15(1):19. Available from: <http://ehjournal.biomedcentral.com/articles/10.1186/s12940-016-0117-0>
- [4] IARC. Some Organophosphate Insecticides and Herbicides. *Int Agency Res Cancer* [Internet]. 2017; Available from: <https://www.ncbi.nlm.nih.gov/books/NBK436774/>
- [5] EFSA. Conclusion on the peer review of the pesticide risk assessment of the active substance glyphosate. *EFSA J* [Internet]. 2015 Nov;13(11):1–107. Available from: <http://doi.wiley.com/10.2903/j.efsa.2015.4302>
- [6] Bonini EA, Marchiosi R, Zonetti P da C, Zobiolo LHS, Ferrarese-Filho O. Chromatographic determination of shikimate for identification of conventional soybean and glyphosate resistant soybean. *Biosci J* [Internet]. 2020 Feb 11;36(2):383–9. Available from: <https://seer.ufu.br/index.php/biosciencejournal/article/view/42339>
- [7] Alibhai MF, Stallings WC. Closing down on glyphosate inhibition—with a new structure for drug discovery. *Proc Natl Acad Sci* [Internet]. 2001 Mar 13;98(6):2944–6. Available from: <https://pnas.org/doi/full/10.1073/pnas.061025898>
- [8] Shilo T, Zygiel L, Rubin B, Wolf S, Eizenberg H. Mechanism of glyphosate control of *Phelipanche aegyptiaca*. *Planta* [Internet]. 2016 Nov 20;244(5):1095–107. Available from: <http://link.springer.com/10.1007/s00425-016-2565-8>
- [9] Lamego FP, Nachtigall JR, Machado YMS, Langer C de O, Polino R do C, Bastiani MO. Resistance of *Amaranthus hybridus* to glyphosate: detection, mechanisms involved and alternatives for integrated management. *Adv Weed Sci* [Internet]. 2024 Oct 17;42. Available from: <https://awsjournal.org/article/resistance-of-amaranthus-hybridus-to-glyphosate-detection-mechanisms-involved-and-alternatives-for-integrated-management/>
- [10] Sammons RD, Gaines TA. Glyphosate resistance: state of knowledge. *Pest Manag Sci* [Internet]. 2014 Sep 12;70(9):1367–77. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/ps.3743>
- [11] Chatham LA, Bradley KW, Kruger GR, Martin JR, Owen MDK, Peterson DE, et al. A Multistate Study of the Association Between Glyphosate Resistance and EPSPS Gene Amplification in Waterhemp (*Amaranthus tuberculatus*). *Weed Sci* [Internet]. 2015 Sep 20;63(3):569–77. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/ps.3743>

- https://www.cambridge.org/core/product/identifier/S0043174500014612/type/journal_article
- [12] Johnson NA, Lemas J, Montgomery J, Gaines T, Patterson E. Genomic structural variation and herbicide resistance. *Can J Plant Sci* [Internet]. 2025 Jan 1;105:1–10. Available from: <https://cdnsiencepub.com/doi/10.1139/cjps-2024-0199>
- [13] Barroso AA, de S Costa MG, Neto NJ, dos Santos JI, Balbuena TS, Carbonari CA, et al. Protein identification before and after glyphosate exposure in *Lolium multiflorum* genotypes. *Pest Manag Sci* [Internet]. 2018 May 16;74(5):1125–33. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/ps.4831>
- [14] Yerka MK, Wiersma AT, Lindenmayer RB, Westra P, Johnson WG, de Leon N, et al. Reduced Translocation Is Associated with Tolerance of Common Lambsquarters (*Chenopodium album*) to Glyphosate. *Weed Sci* [Internet]. 2013 Sep 20;61(3):353–60. Available from: https://www.cambridge.org/core/product/identifier/S0043174500013151/type/journal_article
- [15] Badani H, Djadouni F, Haddad FZ. Effects of the herbicide glyphosate [n-(phosphonomethyl) glycine] on biodiversity and organisms in the soil. *Eur J Environ Sci* [Internet]. 2023 Jun 30;13(1):5–14. Available from: <https://ejes.cz/index.php/ejes/article/view/815>
- [16] Bayata A, Nigussie M, Takala B. Prolonged Glyphosate Application Effects on Soil Microbial Biomass Carbon in Coffee Cultivation Systems: Preliminary Observation. *Innovation* [Internet]. 2025 Apr 27;6(2):39–44. Available from: <https://www.sciencepublishinggroup.com/article/10.11648/j.innov.20250602.12>
- [17] van Bruggen AHC, Finckh MR, He M, Ritsema CJ, Harkes P, Knuth D, et al. Indirect Effects of the Herbicide Glyphosate on Plant, Animal and Human Health Through its Effects on Microbial Communities. *Front Environ Sci* [Internet]. 2021 Oct 18;9. Available from: <https://www.frontiersin.org/articles/10.3389/fenvs.2021.763917/full>
- [18] Leyva-Morales JB, Cabrera R, Bastidas-Bastidas P de J, Valenzuela-Quintanar AI, Pérez-Camarillo JP, González-Mendoza VM, et al. Validation and Application of Liquid Chromatography Coupled with Tandem Mass Spectrometry Method for the Analysis of Glyphosate, Aminomethylphosphonic Acid (AMPA), and Glufosinate in Soil. *Agriculture* [Internet]. 2023 May 27;13(6):1131. Available from: <https://www.mdpi.com/2077-0472/13/6/1131>
- [19] Melas GB, Ortiz O, Roshdy AM, Hendawi MY, Triantakoustantis D, Shaddad S. Assessing the Modulatory Effects of Biochar on Soil Health Status in Response to Pesticide Application. *Earth* [Internet]. 2025 Apr 11;6(2):27. Available from: <https://www.mdpi.com/2673-4834/6/2/27>
- [20] Schomberg AC, Bringezu S, Beusen AWH. Water quality footprint of agricultural emissions of nitrogen, phosphorus and glyphosate associated with German bioeconomy. *Commun Earth Environ* [Internet]. 2023 Nov 2;4(1):404. Available from: <https://www.nature.com/articles/s43247-023-01054-3>
- [21] Gokou Jean Marie Djédjé, Kouakou Gains Kpan Kpan, Dopé Armel Cyrille Yapi, Kouamé Victor Kouamé, Abiba Sanogo Tidou Epse Koné. Impact of Glyphosate and 2,4-D used in agriculture on the quality of *Chrysichthys nigrodigitatus* (Lacépède, 1803) from the Sassandra River in Guessabo (Côte D'ivoire). *World J Adv Res Rev* [Internet]. 2022 Apr 30;14(1):212–22. Available from: <https://wjarr.com/content/impact-glyphosate-and-24-d-used-agriculture-quality-chrysichthys-nigrodigitatus-lacépède>
- [22] Malone RW, Shipitalo MJ, Wauchope RD, Sumner H. Residual and Contact Herbicide Transport through Field Lysimeters via Preferential Flow. *J Environ Qual* [Internet]. 2004 Nov;33(6):2141–8. Available from: <https://access.onlinelibrary.wiley.com/doi/10.2134/jeq2004.2141>
- [23] Singh R, Shukla A, Kaur G, Girdhar M, Malik T, Mohan A. Systemic Analysis of Glyphosate Impact on Environment and Human Health. *ACS Omega*. 2024;09:6165–83.
- [24] Fernández-Peña M de L, Pérez-Vázquez A, Castañeda-Chávez M del R, Díaz-Rivera P, Ortega-Jiménez E, López-Romero G. IMPACTS

- OF GLYPHOSATE (ROUNDUP®) ON THE ENVIRONMENT AND ON HUMAN HEALTH. *Agrociencia* [Internet]. 2023 Jun 7; Available from: <https://agrociencia-colpos.org/index.php/agrociencia/article/view/2844>
- [25] Lozano VL, Pizarro HN. Glyphosate lessons: is biodegradation of pesticides a harmless process for biodiversity? *Environ Sci Eur* [Internet]. 2024 Mar 17;36(1):55. Available from: <https://enveurope.springeropen.com/articles/10.1186/s12302-024-00884-y>
- [26] Ayesha Kaushar, Reshma Sinha. TOXICOLOGICAL IMPACT OF GLYPHOSATE BASED HERBICIDE ON THE SURVIVAL RATE OF DROSOPHILA MELANOGASTER. *Int J Sci Res Mod Sci Technol* [Internet]. 2025 Apr 24;4(4):1–6. Available from: <https://ijsrmst.com/index.php/ijsrmst/article/view/315>
- [27] Wesonga ZM, Bargul JL, Paredes JC, Dubois T, Lattorff HMG. Impact of acute oral exposure to paraquat and glyphosate on food consumption and survival rates of the African honeybee *Apis mellifera scutellata* Lepelletier (Hymenoptera: Apidae). *Int J Trop Insect Sci* [Internet]. 2023 Aug 18;43(5):1513–21. Available from: <https://link.springer.com/10.1007/s42690-023-01064-w>
- [28] Panzacchi S, Tibaldi E, De Angelis L, Falcioni L, Giovannini R, Gnudi F, et al. Carcinogenic effects of long-term exposure from prenatal life to glyphosate and glyphosate-based herbicides in Sprague–Dawley rats. *Environ Heal* [Internet]. 2025 Jun 10;24(1):36. Available from: <https://ehjournal.biomedcentral.com/articles/10.1186/s12940-025-01187-2>
- [29] Solomon KR. Measured exposures to glyphosate in applicators and the general population: an updated review of the scientific literature since 2020. *Pest Manag Sci* [Internet]. 2025 Jun 3; Available from: <https://scijournals.onlinelibrary.wiley.com/doi/10.1002/ps.8901>
- [30] Klátyik S, Simon G, Takács E, Oláh M, Zaller JG, Antoniou MN, et al. Toxicological concerns regarding glyphosate, its formulations, and co-formulants as environmental pollutants: a review of published studies from 2010 to 2025. *Arch Toxicol* [Internet]. 2025 May 26; Available from: <https://link.springer.com/10.1007/s00204-025-04076-2>
- [31] Brookes G, Taheripour F, Tyner WE. The contribution of glyphosate to agriculture and potential impact of restrictions on use at the global level. *GM Crops Food* [Internet]. 2017 Oct 2;8(4):216–28. Available from: <https://www.tandfonline.com/doi/full/10.1080/21645698.2017.1390637>
- [32] IFT. ift. 2017. p. 1 Banning glyphosate may lower crop yield, increase carbon impact. Available from: https://www.ift.org/news-and-publications/scientific-journals/news/2017/december/12/banning-glyphosate-may-lower-crop-yield-increase-carbon-impact?utm_source=chatgpt.com
- [33] Wynn S, Webb E. Impact assessment of the loss of glyphosate within the EU: a literature review. *Environ Sci Eur* [Internet]. 2022 Dec 15;34(1):91. Available from: <https://enveurope.springeropen.com/articles/10.1186/s12302-022-00667-3>
- [34] Clarke P. fwi. 2017. Glyphosate ban would cost UK farmers £1bn a year. Available from: https://www.fwi.co.uk/arable/crop-management/glyphosate-ban-cost-uk-farmers-1bn-year?utm_source=chatgpt.com
- [35] Varma N, Wadatkar H, Salve R, Kumar TV. Advancing Sustainable Agriculture: A Comprehensive Review of Organic Farming Practices and Environmental Impact. *J Exp Agric Int* [Internet]. 2024 Jun 26;46(7):695–703. Available from: <https://journaljeai.com/index.php/JEAI/article/view/2623>