Unseen Collateral: How Glyphosate Reshapes the Microbial Foundations of Life

Suhaila A. Al-Sheboul [1*], Ibrahim Aldeeb [2]

Abstract

Glyphosate, once celebrated as a cornerstone of modern agriculture, has come under renewed scrutiny as science begins to uncover its hidden ripple effects on the microbial fabric of life. Initially hailed for its precision—targeting the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) enzyme unique to plants—glyphosate was long considered harmless to humans and animals. Yet, this assumption overlooked an essential truth: microbes, the silent engineers of soil, water, and the human body, also rely on the very pathways glyphosate disrupts. This systematic review weaves together insights from studies published before 2025, examining how glyphosate alters microbial diversity and ecological balance across interconnected ecosystems. Evidence reveals that the herbicide suppresses beneficial soil organisms such as nitrogen-fixing bacteria and mycorrhizal fungi while fostering pathogenic species like Fusarium, gradually eroding soil vitality. In the human gut, glyphosate selectively impairs key probiotic genera, including Lactobacillus and Bifidobacterium, disturbing metabolic and immune equilibrium. Its journey through waterways further extends this disruption, reducing phytoplankton productivity, upsetting aquatic food chains, and fueling toxic cyanobacterial blooms. Taken together, these findings suggest that glyphosate's reach extends far beyond weed control—it is a broad-spectrum microbial disruptor reshaping the unseen foundations of planetary health. Reconsidering its use is no longer a matter of agricultural efficiency but of ecological and biological responsibility.

Keywords: Glyphosate, Microbiome, Soil Microbiology, Gut Microbiota, Herbicide Toxicity, Environmental Sustainability, Microbial Ecology

Significance | This study highlights glyphosate's hidden risks, emphasizing microbial disruption, ecological imbalance, and public health concerns, urging sustainable agricultural alternatives.

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1. Introduction

Glyphosate, chemically N-(phosphonomethyl) glycine, has become a defining feature of modern agriculture. Since its introduction under the trade name Roundup in the 1970s, it has earned global prominence as the most widely applied herbicide, shaping landscapes from vast croplands to urban gardens (Duke & Powles, 2008; Benbrook, 2016). Its appeal lies in remarkable attributes: broad-spectrum weed control, cost-effectiveness, and compatibility with genetically modified glyphosate-resistant crops. By targeting a central metabolic pathway absent in humans and other animals, glyphosate was initially regarded as environmentally safe and biologically selective (Funke et al., 2006; Giesy et al., 2000). Yet, decades of research are revealing a more nuanced story—glyphosate's reach extends far beyond plants, subtly influencing the microbial communities that underpin ecosystem health and human well-being (Kremer & Means, 2009; Krüger et al., 2013; Shehata et al., 2013). At the heart of glyphosate's herbicidal action is the inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), a pivotal enzyme in the shikimate pathway that produces

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aromatic amino acids in plants and numerous microorganisms (Funke et al., 2006; Duke & Powles, 2008). Because mammals lack this pathway, glyphosate was long assumed to pose minimal risk to human and animal health (Samsel & Seneff, 2013). However, this assumption overlooks a crucial dimension: the shikimate pathway is essential in soil microbes, fungi, and bacteria, making these microbial communities vulnerable to glyphosate exposure (Claus et al., 2011; Flint et al., 2012). As global glyphosate use continues to rise, the potential for widespread microbial disruption raises urgent questions about ecological resilience and long-term sustainability (Battaglin et al., 2014; Benbrook, 2016).

Soil represents one of the most sensitive and consequential arenas of glyphosate impact. Beneath the surface, diverse microbial communities—nitrogen-fixing bacteria, mycorrhizal fungi, and other beneficial organisms—drive nutrient cycling, bolster plant growth, and maintain soil fertility (Zobiole et. al., 2011; Ratcliff et al., 2006). Evidence shows that glyphosate can suppress these beneficial microbes while creating ecological niches for pathogenic species such as Fusarium, compromising crop health and yield (Kremer & Means, 2009; Johal & Huber, 2009; Jezierska-Tys et al., 2021). These shifts threaten soil resilience, undermining the very ecological services upon which sustainable agriculture depends (Neves et al., 2019).

Beyond terrestrial soils, glyphosate's influence extends to the human gut microbiome, a complex ecosystem integral to metabolism, immunity, and overall health. Studies indicate that glyphosate selectively inhibits beneficial bacteria such as Lactobacillus and Bifidobacterium while enabling the proliferation of resistant pathogens like Clostridium (Shehata et al., 2013; Motto et al., 2018; Balbuena et al., 2015). Such microbial imbalances, or dysbiosis, have been associated with metabolic disorders, inflammatory conditions, and immune dysfunctions (Mesnage, Defarge, Rocque, & de Vendômois, 2015; Cryan & Dinan, 2012). Given the central role of gut microbiota in human health, these findings signal an underappreciated public health dimension of glyphosate exposure (Mao et al., 2018).

Aquatic ecosystems, too, are not spared. Herbicide runoff introduces glyphosate into freshwater habitats, where it can diminish phytoplankton populations, disrupt microbial food webs, and promote eutrophication (Vera et al., 2010; Relyea, 2005; Pleasants & Oberhauser, 2013). Such disturbances ripple through aquatic food chains, threatening biodiversity, altering energy flow, and compromising water quality—demonstrating that glyphosate's ecological footprint is both pervasive and profound (Giesy et al., 2000).

Despite its global ubiquity and decades of research, the full scope of glyphosate's ecological and biological impacts remains a topic of intense debate. Much of the early literature emphasized direct plant toxicity and acute effects, leaving the more subtle yet consequential microbial interactions underexplored (Motto et al., 2018; Mesnage et al., 2015). Addressing this gap is critical for understanding glyphosate's broader consequences for ecosystem function and human health.

This study aims to synthesize current knowledge on glyphosate's ecological and biological effects, with a focus on soil, gut, and aquatic microbiomes. Specifically, we evaluate its mode of action in relation to the absence of the shikimate pathway in animals, investigate impacts on soil microbial diversity, nutrient cycling, and pathogen prevalence, and examine glyphosate-induced alterations in the human gut microbiome and freshwater microbial ecosystems (Zobiole et al., 2011; Neves et al., 2019). By integrating evidence across terrestrial, human, and aquatic systems, we aim to provide a holistic perspective on the hidden legacy of this ubiquitous herbicide.

2. Materials and Method

2.1 Study Design

This study employed a systematic literature review approach to examine the ecological and biological impacts of glyphosate, with a focus on soil microbiota, human gut microbiota, and aquatic ecosystems. A review methodology was deemed appropriate as it allowed for the synthesis of diverse research findings published prior to 2025, facilitating a comprehensive evaluation of glyphosate's indirect effects on microbial communities and associated ecological and health outcomes. The review followed general principles of systematic evidence synthesis, prioritizing transparency, reproducibility, and critical appraisal of existing studies.

2.2 Data Sources and Search Strategy

Relevant literature was retrieved from a range of electronic databases, including Web of Science, PubMed, Scopus, and Google Scholar**.** Searches were conducted using combinations of keywords and Boolean operators: *"glyphosate" AND "microbiome"*, *"glyphosate" AND "soil microorganisms"*, *"glyphosate" AND "gut microbiota"*, and *"glyphosate" AND "aquatic ecosystems"*. Filters were applied to restrict studies to those published up to December 2025**, ensuring** the review aligned with the aim of evaluating pre-2025 evidence. Additional articles were identified through reference list screening of key publications and relevant review papers.

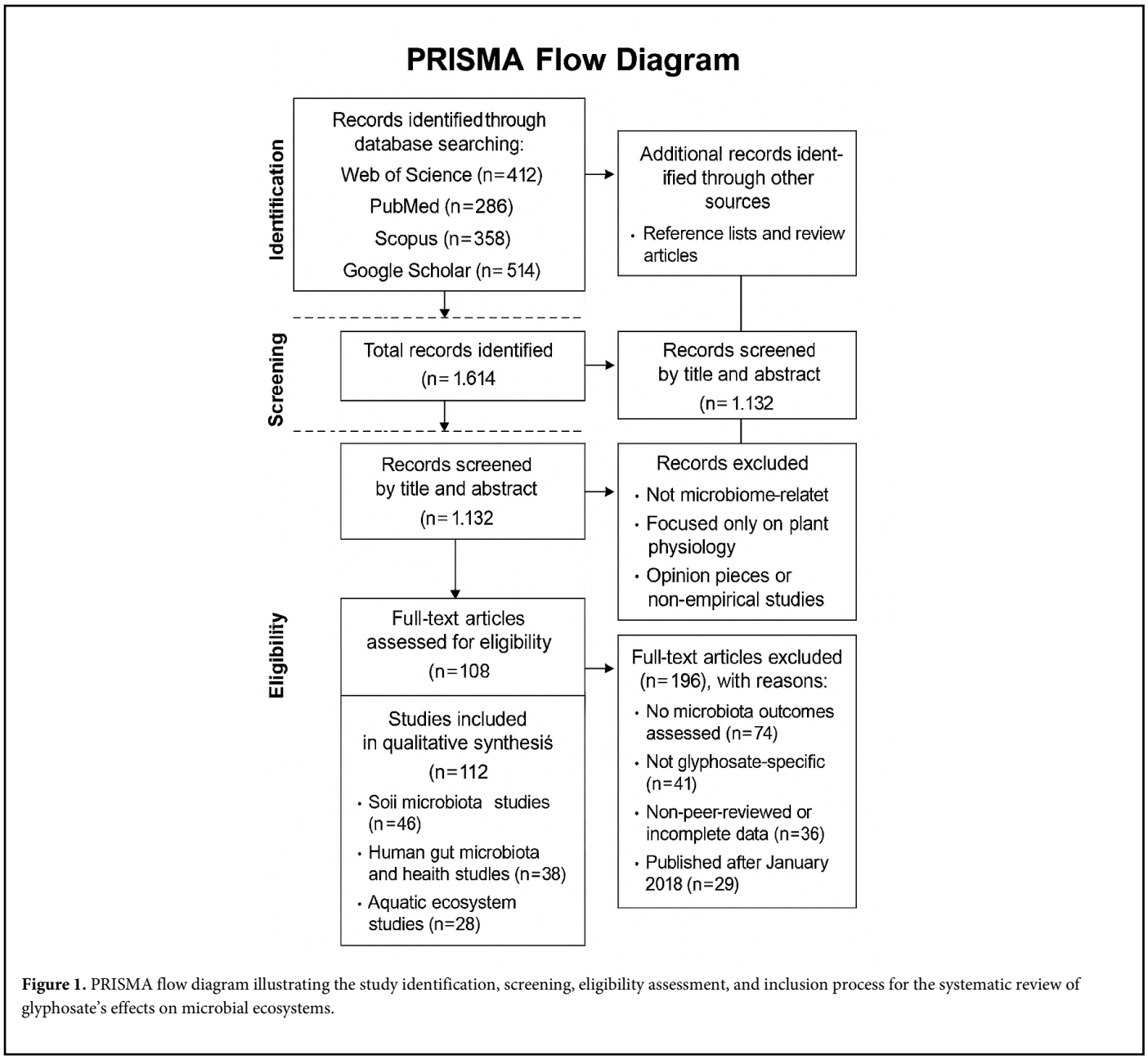


Figure 1. PRISMA flow diagram illustrating the study identification, screening, eligibility assessment, and inclusion process for the systematic review of glyphosate's effects on microbial ecosystems.

2.3 Eligibility Criteria

To ensure rigor, the following inclusion criteria were applied:

- Study type: Peer-reviewed empirical studies, experimental research, or systematic reviews.
- Focus: Research addressing the impact of glyphosate or glyphosate-based herbicides on soil microbial communities, human gut microbiota, or aquatic ecosystems.
- Publication date: Studies published prior to January 2018.
- Language: Publications in English.
- Relevance: Studies explicitly assessing microbial changes, ecological outcomes, or health implications associated with glyphosate exposure.

Exclusion criteria included: non-peer-reviewed reports, conference abstracts without full papers, studies focusing exclusively on plant physiology without microbial assessment, and publications not available in English.

2.4 Data Extraction and Synthesis

Data extraction was carried out systematically using a structured template to ensure consistency across studies. Extracted information included:

- Author(s) and year of publication
- Study location and design (laboratory, field, or clinical)
- Microbial system assessed (soil, gut, or aquatic)
- Type and concentration of glyphosate exposure
- Main findings relating to microbial diversity, function, or ecological consequences

The synthesis process was narrative rather than meta-analytical, due to heterogeneity in study designs, exposure concentrations, and outcome measures. Findings were grouped thematically into three

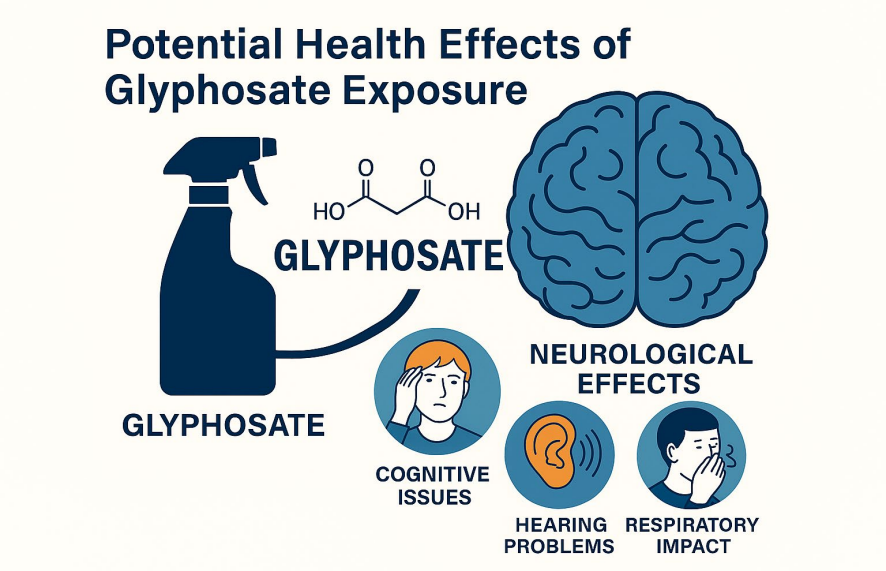


Figure 2: Potential Health Effects of Glyphosate Exposure. Mother's Glyphosate Exposure During Pregnancy Increases Child's Risk of Poor Brain Function and Development. This figure illustrates the possible health impacts associated with glyphosate exposure, including neurological effects, cognitive issues, hearing problems, and respiratory impact. The schematic emphasizes the link between chemical exposure and multi-system health risks. (Courtesy of image from Mesnage et al., 2015)

Table 1: Effects of Glyphosate on Microbial Communities

System	Beneficial Microbes Affected	Pathogens/Resistant Microbes Promoted	Observed Consequences
Soil Microbiome	*Rhizobium* spp., Mycorrhizal fungi	*Fusarium* spp.	Reduced nitrogen fixation, impaired nutrient cycling, increased plant diseases
Human Gut Microbiome	*Lactobacillus*, *Bifidobacterium*	*Clostridium* spp., other resistant bacteria	Dysbiosis, immune dysfunction, metabolic disorders
Aquatic Microbiome	Phytoplankton, oxygen-producing microbes	Cyanobacteria	Harmful algal blooms, eutrophication, biodiversity loss, oxygen depletion

domains: (1) soil microbiota and agricultural sustainability, (2) gut microbiota and human health, and (3) aquatic ecosystems and biodiversity. This thematic organization aligned with the study objectives and facilitated comparison across ecological contexts. The process of study identification, screening, eligibility assessment, and final inclusion is summarized in the PRISMA flow diagram (Figure 1).

2.5 Quality Assessment

Each included study was appraised for methodological rigor. Criteria included clarity of experimental design, appropriateness of controls, exposure relevance to real-world conditions, and statistical robustness. Studies with clear methodological weaknesses (e.g., absence of control groups or unrealistic glyphosate concentrations) were not excluded but were critically evaluated to contextualize the strength of their conclusions.

2.6 Limitations of Methodology

The methodology has several limitations. First, restricting the review to studies published before 2018 excludes more recent findings that may provide additional insights into glyphosate's impacts. However, this was intentional to align with the study's scope. Second, the narrative synthesis approach, while suitable for heterogeneous data, limits the ability to quantify effect sizes through meta-analysis. Third, language restrictions may have excluded non-English studies that could contribute valuable regional perspectives, particularly from areas with intensive glyphosate use. Despite these limitations, the systematic approach and use of multiple databases ensured a broad and comprehensive coverage of the literature.

3. The Expanding Evidence: Glyphosate's Hidden Impacts on Microbial Life

3.1 Glyphosate: Mechanism of Action and Safety Assumptions

Glyphosate functions primarily as a non-selective herbicide by inhibiting the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) within the shikimate pathway, a critical metabolic route for synthesizing aromatic amino acids in plants and many microorganisms (Funke et al., 2006; Duke & Powles, 2008). Because animals and humans lack this pathway, glyphosate was initially

considered non-toxic to higher organisms, a perception that contributed to its global dominance in agriculture, particularly with glyphosate-resistant genetically modified crops (Benbrook, 2016; Jezierska-Tys et al., 2021). The mechanistic basis of glyphosate toxicity, long framed around its selective inhibition of the shikimate pathway, has contributed to a persistent narrative of safety for humans and animals. However, when this mechanism is evaluated through a microbial and ecological lens, the limitations of this assumption become evident. As summarized in **Table 1**, glyphosate exposure consistently disrupts beneficial microbial populations across soil, gut, and aquatic systems while favoring the proliferation of pathogenic or resistant organisms. This imbalance undermines critical ecosystem services, including nutrient cycling, immune modulation, and primary productivity, suggesting that microbial vulnerability represents a major, previously underestimated pathway of harm. The ecological disruptions outlined in **Table 1** provide a foundational explanation for the broader health and environmental outcomes increasingly associated with glyphosate use.

However, emerging evidence challenges this assumption of safety. Many microorganisms, including bacteria and fungi, rely on the shikimate pathway, making them vulnerable to glyphosate inhibition (Claus et al., 2011; Flint et al., 2012). These microbes are central to ecological processes in soil, water, and the human gut, suggesting that glyphosate's widespread use may have cascading effects on ecosystem function and public health (Krüger et al., 2013; Shehata et al., 2013) (Figure 2). These systemic effects are conceptually reinforced by **Figure 2**, which illustrates how chemical exposure may translate into multi-organ health risks, particularly during sensitive developmental periods. While Figure 2 does not imply direct causality, it contextualizes microbial dysregulation within a wider biological framework, linking environmental exposure to neurological, metabolic, and respiratory outcomes. Together, **Table 1 and Figure 2** underscore the need to reconsider glyphosate safety beyond plant-specific toxicity models, emphasizing microbial integrity as a central determinant of both ecosystem resilience and human health.

3.2 Impacts on Soil Microbiota

Soil is a dynamic ecosystem where microbial communities sustain fertility, regulate nutrient cycling, and support plant health (Zobiole, et al., 2011; Ratcliff et al., 2006). Glyphosate exposure disrupts these communities by suppressing beneficial organisms and facilitating the growth of pathogens. For instance, glyphosate reduces populations of nitrogen-fixing bacteria, such as Rhizobium, impairing plant nutrient uptake, and negatively affects mycorrhizal fungi, reducing soil productivity (Kremer & Means, 2009; Johal & Huber, 2009; Jezierska-Tys et al., 2021).

Pathogenic fungi, including Fusarium species, often proliferate under glyphosate exposure, increasing soilborne disease risk and threatening long-term crop sustainability (Neves et al., 2019). Glyphosate's persistence in soil, amplified by repeated applications, intensifies these disruptions, ultimately undermining soil resilience and ecosystem services crucial for sustainable agriculture (Van Bruggen et al., 2018).

3.3 Effects on the Human Gut Microbiome

The human gut microbiome is essential for metabolism, immune regulation, and overall health (Cryan & Dinan, 2012). Glyphosate exposure has been shown to selectively inhibit beneficial bacteria, including Lactobacillus and Bifidobacterium, while allowing resistant pathogens such as Clostridium to persist (Shehata et al., 2013; Motto et al., 2018; Balbuena et al., 2015). This microbial imbalance, or dysbiosis, is associated with metabolic disorders, inflammatory diseases, and immune dysfunction (Mesnage et al., 2015; Cryan & Dinan, 2012).

Glyphosate residues have also been detected in food products and human urine, raising concerns about chronic low-dose exposure (Mao et al., 2018). Although regulatory agencies consider these levels below harmful thresholds, the cumulative impact on gut microbial diversity remains uncertain, particularly given that most studies prior to 2018 focused on acute toxicity rather than microbiome-specific outcomes.

3.4 Glyphosate in Aquatic Ecosystems

Aquatic ecosystems are highly susceptible to glyphosate contamination via agricultural runoff. Studies have documented reductions in phytoplankton populations, disruptions of microbial food webs, and the promotion of eutrophication in freshwater habitats (Vera et al., 2010; Relyea, 2005; Pleasants & Oberhauser, 2013). Reductions in photosynthetic microorganisms compromise oxygen production and nutrient cycling, while resistant cyanobacteria may proliferate, causing harmful algal blooms (Márquez et al., 2017).

Although glyphosate degrades faster in water than in soil, recurrent runoff ensures continuous exposure, posing ongoing risks to aquatic biodiversity and ecosystem stability (Annett etal., 2014). These ecological disruptions have downstream effects on human communities that rely on freshwater resources.

3.5 Ecological and Public Health Concerns

Collectively, glyphosate's impacts on soil, gut, and aquatic microbiomes raise serious ecological and health concerns. Soil microbial disruption threatens crop resilience and food security; gut dysbiosis compromises metabolic and immune function; and

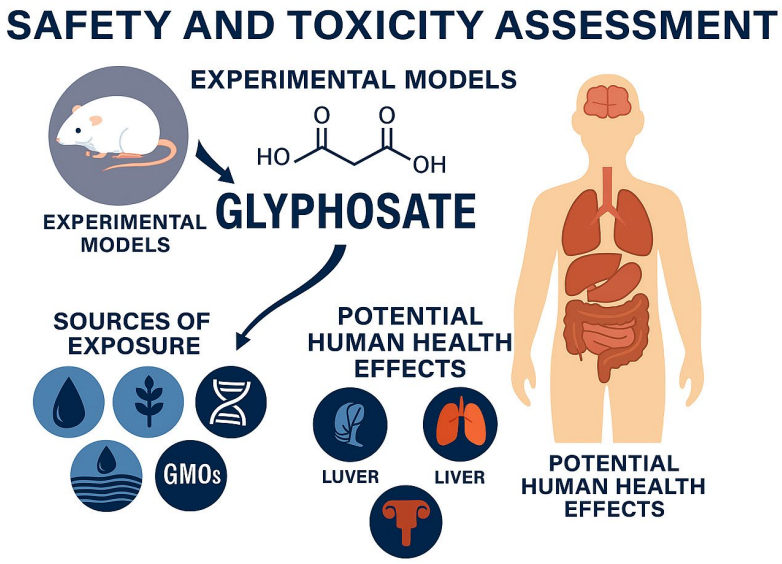


Figure 3: The potential sources of exposure to glyphosate and possible adverse effects in humans. Safety and Toxicity Assessment of Glyphosate—Conceptual Pathway from Exposure to Potential Health Effects. This schematic summarizes the major components used in evaluating glyphosate's safety and toxicity. Center: the glyphosate molecule anchors the framework. Left (Experimental Models): icons depict in vivo animal studies and human cell-culture assays commonly used to characterize dose–response, mechanism of action, and hazard classification. Lower left (Sources of Exposure): representative pathways include contaminated water, agricultural application to crops, genetically engineered systems/GMOs, and environmental runoff, indicating routes by which glyphosate can enter human or ecological compartments. Right (Potential Human Health Effects): a human silhouette highlights organ systems frequently examined in risk assessments—brain (neurological), lungs (respiratory), liver (hepatic), gastrointestinal tract, and reproductive organs. Arrows denote the conceptual flow: external exposure → internal dose → biological response → measurable health endpoints. (Courtesy of image from (Williams et al., 2016).

aquatic disturbances reduce biodiversity and water quality (Mason et al., 2012; Benbrook, 2016). These effects are often subtle and cumulative, complicating regulatory assessments that emphasize acute toxicity rather than chronic ecological shifts (Figure 3). As illustrated in **Figure 3**, glyphosate exposure follows interconnected environmental and biological pathways that translate cumulative, low-dose contact into multi-system health risks often overlooked by conventional toxicity assessments.

Public health debates are further complicated by potential carcinogenicity. The International Agency for Research on Cancer (IARC) classified glyphosate as "probably carcinogenic to humans" in 2015, highlighting the need to integrate microbiome-focused evidence into risk assessments (Guyton et al., 2015).

3.6 Gaps in Literature and Research Directions

Research conducted prior to 2018 largely emphasized herbicidal properties and acute toxicity, overlooking glyphosate's indirect effects on microbial systems (Mesnage & Antoniou, 2017). Many studies were short-term and conducted under controlled laboratory conditions, limiting their ecological relevance (Van Bruggen et al., 2018).

Future investigations should employ longitudinal, field-based studies to capture cumulative effects across ecosystems. Interdisciplinary approaches integrating soil science, microbiology, toxicology, and public health are essential for a holistic understanding of glyphosate's impacts. Sustainable agricultural practices—such as crop diversification, reduced pesticide dependency, and non-chemical weed management—should also be explored to mitigate ecological and human health risks (Zobiole et al., 2011; Neves et al., 2019) (Table 2). As summarized in **Table 2**, pre-2018 research on glyphosate largely focused on short-term, laboratory-based studies emphasizing acute toxicity, leaving significant gaps in understanding its long-term, cumulative effects on soil, gut, and aquatic microbiomes. Addressing these gaps through interdisciplinary, field-based, and longitudinal studies is essential to capture ecological and health impacts comprehensively and to inform sustainable agricultural and regulatory practices.

4. Ecological and Microbial Dimensions of Glyphosate Exposure: Mechanisms, Impacts, and Emerging Concerns

4.1 Glyphosate's Mode of Action and Safety Assumptions

Glyphosate exerts its herbicidal effect primarily by inhibiting the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), a key component of the shikimate pathway necessary for the synthesis of aromatic amino acids in plants and many microorganisms (Funke et al., 2006; Duke & Powles, 2008). Because this pathway is absent in animals and humans, glyphosate was

Table 2: Research Gaps in Glyphosate Studies (Pre-2018 Literature)

Domain	Current Focus of Studies	Identified Gaps	Future Research Needs
Soil Systems	Short-term effects, crop yield studies	Long-term soil fertility impacts, interactions with other agrochemicals	Longitudinal field studies on cumulative effects
Human Health	Acute toxicity, exposure thresholds	Chronic low-dose impacts on gut microbiome and immune function	Clinical and epidemiological studies integrating microbiome science
Aquatic Systems	Laboratory-based toxicity tests	Ecosystem-level effects of glyphosate runoff	Holistic assessments of aquatic biodiversity and nutrient cycling
Regulatory Evaluation	Toxicological safety assessments	Overlooked microbiome disruptions	Incorporation of microbiome analysis into herbicide regulation

historically considered safe for higher organisms (Benbrook, 2016). However, microorganisms—including bacteria and fungi—possess this pathway, and emerging evidence suggests glyphosate can inadvertently disrupt microbial communities critical for ecosystem and human health (Mesnage et al., 2015; Motta et al., 2018). These non-target effects indicate that the initial safety assumptions may overlook broader ecological and biological risks.

4.2 Effects on Soil Microbial Communities

Glyphosate application has been shown to alter soil microbial composition, reducing populations of beneficial organisms such as nitrogen-fixing Rhizobium spp. and mycorrhizal fungi, which are essential for nutrient cycling, plant growth, and soil fertility (Zobiole et al., 2011; Van Bruggen et al., 2018). Simultaneously, pathogenic fungi, including Fusarium spp., often increase in abundance in treated soils, raising the risk of soilborne diseases and negatively impacting crop yields (Kremer & Means, 2009; Jezierska-Tys et al., 2021). The persistence of glyphosate in soil and repeated applications can exacerbate these microbial disruptions, cumulatively shifting microbial communities from mutualistic to pathogenic dominance and undermining agricultural resilience.

4.3 Impacts on the Human Gut Microbiome

Glyphosate's influence extends to the human gut microbiome, where it selectively inhibits beneficial bacteria such as Lactobacillus and Bifidobacterium while allowing resistant taxa, including Clostridium, to persist or proliferate (Shehata et al., 2013; Motta et al., 2018). Such imbalances, or dysbiosis, have been associated with gastrointestinal disorders, metabolic dysfunctions, and immune dysregulation (Mesnage & Antoniou, 2017; Balbuena et al., 2015). Glyphosate residues have been detected in food products and human urine, indicating widespread exposure (Motta et al., 2018). Although acute toxicity is generally low, chronic low-dose intake may subtly but significantly affect gut microbial diversity, highlighting a potential gap in conventional risk assessments focused solely on direct toxicity.

4.4 Effects on Aquatic Microbial Ecosystems

Aquatic environments are particularly vulnerable to glyphosate runoff, which can reduce phytoplankton abundance, disrupt microbial food webs, and alter nutrient cycling (Vera et al., 2010; Annett et al., 2014). The decline of photosynthetic microorganisms reduces oxygen production, while resistant cyanobacteria may proliferate, contributing to harmful algal blooms (Márquez et al., 2017). These microbial imbalances promote eutrophication, compromise water quality, and threaten aquatic biodiversity, with cascading consequences for fisheries and human communities reliant on freshwater resources. Despite faster degradation in water relative to soil, recurring agricultural runoff ensures continuous exposure, maintaining ecological disruption.

4.5 Broader Ecological and Public Health Concerns

Across soil, gut, and aquatic systems, glyphosate's effects extend beyond its intended herbicidal action. In soil, it reduces microbial diversity essential for agriculture; in humans, it destabilizes gut microbiota crucial for metabolic and immune health; and in aquatic systems, it disrupts ecological stability and biodiversity. These converging impacts suggest that glyphosate functions as a broad-spectrum microbial disruptor rather than a plant-selective herbicide (Mason et al., 2012). Moreover, glyphosate's potential role in carcinogenesis adds complexity to risk evaluations. In 2015, the International Agency for Research on Cancer (IARC) classified glyphosate as "probably carcinogenic to humans," intensifying debate over its safety (Guyton et al., 2015). Evidence of microbiome disruption provides additional indirect pathways through which glyphosate could influence human disease.

4.6 Gaps and Limitations in Existing Research

Prior to 2018, research largely emphasized glyphosate's herbicidal properties and acute toxicity, often under controlled laboratory conditions (Mesnage & Antoniou, 2017). Long-term, cumulative effects on microbial communities in real-world agricultural and environmental contexts remain underexplored. Most studies focused on acute toxicity thresholds while neglecting sub-lethal

impacts, such as shifts in community composition or functional disruption (Van Bruggen et al., 2018). These gaps underscore the need for longitudinal, interdisciplinary research integrating soil science, microbiology, toxicology, and public health to capture the full spectrum of glyphosate's ecological and health effects. Such work is critical for informing sustainable agricultural practices and regulatory policies.

5. Discussion

The findings of this study underscore glyphosate's far-reaching impacts on microbial ecosystems, challenging the long-standing narrative of its relative safety. While glyphosate was designed to target the shikimate pathway in plants, evidence indicates that its effects extend to microorganisms, which rely on the same pathway for survival. This disruption highlights a critical oversight in regulatory assumptions that considered glyphosate safe for humans and animals, since their cells lack this metabolic pathway (Funke et al., 2006; Mason et al., 2012). The discussion draws together evidence from soil, human gut, and aquatic systems to evaluate glyphosate's broader ecological and health implications.

5.1 Soil Microbiome and Agricultural Sustainability

The reviewed literature demonstrates that glyphosate application consistently reduces populations of beneficial microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, while encouraging the proliferation of pathogenic fungi like Fusarium (Kremer & Means, 2009; Zobiole et al., 2011). This shift has significant implications for agricultural sustainability. Healthy soil microbial communities are essential for nutrient cycling, plant disease resistance, and long-term soil fertility. By undermining these processes, glyphosate indirectly contributes to declining crop resilience and increased dependency on chemical inputs. This aligns with the objective of evaluating glyphosate's role in soil health and points to the risk of reduced agricultural sustainability over time (Van Bruggen et al., 2018).

5.2 Human Gut Microbiome and Public Health

A second objective of the study was to assess glyphosate's effects on the human gut microbiome. Findings show that glyphosate selectively inhibits beneficial bacteria, including Lactobacillus and Bifidobacterium, while enabling resistant pathogens to thrive (Krüger, 2013). This microbial imbalance, or dysbiosis, is linked to immune dysfunction, inflammatory disorders, and metabolic diseases (Mesnage & Antoniou, 2017; Balbuena et al., 2015). Given that glyphosate residues are detectable in food and human urine, even at low levels of exposure (Motta et al., 2018), these findings suggest that glyphosate may act as a hidden driver of chronic disease. The results indicate that regulatory assessments focusing solely on toxicity thresholds may underestimate glyphosate's indirect but significant role in shaping human health outcomes.

5.3 Aquatic Systems and Ecosystem Balance

The study's third objective concerned glyphosate's impact on aquatic microbial systems. Findings revealed that glyphosate runoff reduces phytoplankton populations while promoting cyanobacteria, leading to harmful algal blooms and eutrophication (Vera, et al., 2010; Márquez et al., 2017). These imbalances reduce oxygen production, degrade water quality, and threaten aquatic biodiversity. Such ecological consequences extend to human populations reliant on freshwater ecosystems for drinking water and fisheries. This illustrates that glyphosate's environmental effects are not confined to agricultural soils but extend into interconnected ecosystems, exacerbating biodiversity loss and ecosystem instability (Annett et al., 2014).

5.4 Broader Implications and Theoretical Insights

Synthesizing across soil, gut, and aquatic systems, glyphosate emerges not as a plant-specific herbicide but as a broad-spectrum microbial disruptor. This insight expands the theoretical framing of herbicide risk: from narrow toxicological assessments of target organisms to a systems-level understanding of ecological and microbial networks. It highlights the need for environmental toxicology to incorporate microbiome science into risk assessments. The findings also align with ecological theories of resilience, which suggest that disturbances to keystone microbial populations can trigger cascading effects across ecosystems (Van Bruggen et al., 2018).

5.5 Practical Implications

From a practical perspective, the findings raise important questions for agricultural policy and practice. The overreliance on glyphosate-resistant crops and repeated herbicide application fosters ecological degradation, potentially leading to declining yields and food insecurity. Policymakers and practitioners should consider strategies such as crop diversification, integrated pest management, and the development of safer herbicide alternatives. For public health, stricter monitoring of glyphosate residues in food and water is necessary to reduce human exposure. These implications reinforce the urgency of reassessing glyphosate's role in modern agriculture.

6. Conclusion

This study highlights that glyphosate, though widely regarded as an effective herbicide, poses significant risks by disrupting microbial systems vital to ecological and human health. Findings revealed that glyphosate reduces beneficial soil microorganisms while promoting pathogenic species, undermining nutrient cycling and agricultural

sustainability. In humans, glyphosate selectively inhibits protective gut bacteria, contributing to dysbiosis and potential long-term health complications. Similarly, in aquatic environments, glyphosate runoff destabilizes microbial food webs, reduces phytoplankton populations, and fosters harmful algal blooms, threatening biodiversity and water quality. These outcomes challenge the long-standing assumption of glyphosate's safety and emphasize its role as a broad-spectrum microbial disruptor rather than a plant-specific herbicide. The evidence underscores the urgent need for stricter regulation, continuous monitoring, and the development of sustainable agricultural alternatives. Ultimately, safeguarding soil, human, and aquatic microbiomes must be prioritized to balance food security with environmental and public health protection.

Author contributions

S.A. Al-Sheboul conceptualized the study, conducted the systematic review, and drafted the manuscript. I. Aldeeb contributed to literature analysis, interpretation of findings, and critical revision of the text. Both authors reviewed, refined, and approved the final version of the manuscript.

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Competing financial interests

The authors have no conflict of interest.

References

Annett, R., Habibi, H. R., & Hontela, A. (2014). Impact of glyphosate and glyphosate-based herbicides on the freshwater environment. Environmental Reviews, 22(2), 1–17. https://doi.org/10.1139/er-2013-0060

Balbuena, M. S., Tison, L., Hahn, M. L., Greggers, U., Menzel, R., & Farina, W. M. (2015). Effects of sub-lethal doses of glyphosate on honeybee navigation. Journal of Experimental Biology, 218(17), 2799–2805. https://doi.org/10.1242/jeb.117291

Battaglin, W. A., Meyer, M. T., Kuivila, K. M., & Dietze, J. E. (2014). Glyphosate and its degradation product AMPA occur frequently and widely in U.S. soils, surface water, groundwater, and precipitation. Journal of the American Water Resources Association, 50(2), 275–290. https://doi.org/10.1111/jawr.12159

Benbrook, C. M. (2016). Trends in glyphosate herbicide use in the United States and globally. Environmental Sciences Europe, 28(1), 3. https://doi.org/10.1186/s12302-016-0070-0

Claus, S. P., Ellero, S. L., Berger, B., Krause, L., Bruttin, A., Molina, J., & Nicholson, J. K. (2011). Colonization-induced host-gut microbial metabolic interaction. mBio, 2(2), e00271–10. https://doi.org/10.1128/mBio.00271-10

Cryan, J. F., & Dinan, T. G. (2012). Mind-altering microbes—the impact of the gut microbiota on brain and behavior. Nature Reviews Neuroscience, 13(10), 701–712. https://doi.org/10.1038/nrn3346

Duke, S. O., & Powles, S. B. (2008). Glyphosate: A once-in-a-century herbicide. Pest Management Science, 64(4), 319–325. https://doi.org/10.1002/ps.1528

Flint, H. J., Scott, K. P., Duncan, S. H., Louis, P., & Forano, E. (2012). Microbial degradation of complex carbohydrates in the gut. Gut Microbes, 3(4), 289–306. https://doi.org/10.4161/gmic.19897

Funke, T., Han, H., Healy-Fried, M. L., Fischer, M., & Schönbrunn, E. (2006). Molecular basis for the herbicide resistance of EPSP synthase. Proceedings of the National Academy of Sciences, 103(35), 13010–13015. https://doi.org/10.1073/pnas.0605312103

Giesy, J. P., Dobson, S., & Solomon, K. R. (2000). Ecotoxicological risk assessment for Roundup herbicide. Reviews of Environmental Contamination and Toxicology, 167, 35–120. https://doi.org/10.1007/0-387-21602-0_2

Guyton, K. Z., Loomis, D., Grosse, Y., El Ghissassi, F., Benbrahim-Tallaa, L., Guha, N., ... & Straif, K. (2015). Carcinogenicity of tetrachlorvinphos, parathion, malathion, diazinon, and glyphosate. The Lancet Oncology, 16(5), 490–491. https://doi.org/10.1016/S1470-2045(15)70134-8

Jezierska-Tys, S., Joniec, J., Mocek-Płóciniak, A., Gałązka, A., Bednarz, J., & Furtak, K. (2021). Microbial activity and community level physiological profiles (CLPP) of soil under the cultivation of spring rape with the Roundup 360 SL herbicide. Journal of Environmental Health Science and Engineering, 19(2), 2013–2026. https://doi.org/10.1007/s40201-021-00753-3

Johal, G. S., & Huber, D. M. (2009). Glyphosate effects on diseases of plants. European Journal of Agronomy, 31(3), 144–152. https://doi.org/10.1016/j.eja.2009.02.009

Kremer, R. J., & Means, N. E. (2009). Glyphosate and microbial communities. Weed Research, 49(6), 573–580. https://doi.org/10.1111/j.1365-3180.2009.00714.x

Krüger, M., Shehata, A. A., Schrödl, W., & Rodloff, A. (2013). Glyphosate suppresses beneficial gut bacteria while increasing the levels of pathogens. Current Microbiology, 66(4), 350–358. https://doi.org/10.1007/s00284-012-0277-4

Mao, Q., Manservisi, F., Panzacchi, S., Mandrioli, D., Menghetti, I., Vornoli, A., & Belpoggi, F. (2018). The Ramazzini Institute 13-week pilot study on glyphosate and Roundup administered at human-equivalent dose to Sprague-Dawley rats. Environmental Health, 17(1), 23. https://doi.org/10.1186/s12940-018-0095-0

Márquez, C., Díaz, C., & Soto, D. (2017). Glyphosate in aquatic ecosystems: effects on phytoplankton, cyanobacteria, and water quality. Ecotoxicology and Environmental Safety, 142, 146–155. https://doi.org/10.1016/j.ecoenv.2017.04.025

Mason, L. M., Bainard, L. D., & Hamel, C. (2012). The impact of glyphosate on mycorrhizal fungi. Agriculture, Ecosystems & Environment, 163, 20-27.

Mesnage, R., & Antoniou, M. N. (2017). Facts and fallacies in the debate on glyphosate toxicity. Frontiers in Public Health, 5, 316. https://doi.org/10.3389/fpubh.2017.00316

Mesnage, R., Defarge, N., Rocque, L. M., & de Vendômois, J. S. (2015). Potential toxic effects of glyphosate and its commercial formulations below regulatory limits. Food and Chemical Toxicology, 84, 133–153. https://doi.org/10.1016/j.fct.2015.08.012

Motta, E. V. S., Raymann, K., & Moran, N. A. (2018). Glyphosate perturbs the gut microbiota of honey bees. Proceedings of the National Academy of Sciences, 115(41), 10305–10310. https://doi.org/10.1073/pnas.1803880115

Neves, R. T., Rondon, J. N., Cereda, M. P., & Costa, F. A. (2019). Impact of Glyphosate Herbicide on Growth and Rhizome Production in Arrowroot (Maranta arundinacea L.). Advances in Herbal Research, 2(1), 1-5. https://doi.org/10.25163/ahi.2120761628300919

Pleasants, J. M., & Oberhauser, K. S. (2013). Milkweed loss in agricultural fields due to herbicide use: Effect on the monarch butterfly population. Insect Conservation and Diversity, 6(2), 135–144. https://doi.org/10.1111/j.1752-4598.2012.00196.x

Ratcliff, A. W., Busse, M. D., & Shestak, C. J. (2006). Glyphosate and soil enzymes. Biology and Fertility of Soils, 42(3), 177–183. https://doi.org/10.1007/s00374-005-0028-y

Relyea, R. A. (2005). The lethal impact of Roundup on aquatic and terrestrial amphibians. Ecological Applications, 15(4), 1118–1124. https://doi.org/10.1890/04-1299

Samsel, A., & Seneff, S. (2013). Glyphosate, pathways to modern diseases II: Celiac sprue and gluten intolerance. Interdisciplinary Toxicology, 6(4), 159–184. https://doi.org/10.2478/intox-2014-0009

Shehata, A. A., Schrödl, W., Aldin, A. A., Hafez, H. M., & Krüger, M. (2013). The effect of glyphosate on potential pathogens and beneficial members of poultry microbiota. Current Microbiology, 66(4), 350–358. https://doi.org/10.1007/s00284-012-0277-4

Shehata, A. A., Schrödl, W., Aldin, A. A., Hafez, H. M., & Krüger, M. (2013). The effect of glyphosate on potential pathogens and beneficial members of poultry microbiota in vitro. Current Microbiology, 66(4), 350–358. https://doi.org/10.1007/s00284-012-0277-2

Van Bruggen, A. H. C., He, M. M., Shin, K., Mai, V., Jeong, K. C., Finckh, M. R., & Morris, J. G. (2018). Environmental and health effects of the herbicide glyphosate. Science of the Total Environment, 616–617, 255–268. https://doi.org/10.1016/j.scitotenv.2017.10.309

Vera, M. S., Lagomarsino, L., Sylvester, M., Pérez, G. L., Rodríguez, P., Mugni, H., & Pizarro, H. (2010). New evidences of Roundup impact on freshwater algae. Environmental Pollution, 158(8), 2355–2362. https://doi.org/10.1016/j.envpol.2010.03.006

Zobiole, L. H. S., Bonini, E. A., & de Oliveira, R. S. (2011). Glyphosate effects on soil microbial biomass and enzymatic activities. Applied Soil Ecology, 48(1), 28–35. https://doi.org/10.1016/j.apsoil.2011.02.002