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Biodegradation of Glufosinate Ammonium in Agricultural Soil: A short review of Microbial Strategies for Sustainable Herbicide Remediation

Kabiru Yakubu[1,4*], Salihu Ibrahim[2], Ahmad Umar Bello[1] and Abba Babandi[1,3]

[1]Department of Biochemistry, Faculty of Basic Medical Sciences, Bayero University, Kano, PMB 3011, Gwarzo Road, Kano State, Nigeria.

[2]Centre for Biotechnology Research, Bayero University, Kano, PMB 3011, Gwarzo Road, Kano State, Nigeria.

[3]Medical Biochemistry Unit, Faculty of Basic Medical Sciences, Federal University Dutse, PMB 7156, Dutse, Jigawa State-Nigeria

[4]Department of Botany, Faculty of Science, Adamawa State University, Mubi P.M.B 25 Mubi, Adamawa State. Nigeria.

Corresponding Author: Kabiru Yakubu, Department of Biochemistry, Faculty of Basic Medical Sciences, Bayero University, Kano, PMB 3011, Gwarzo Road, Kano State, Nigeria. Department of Botany, Faculty of Science, Adamawa State University, Mubi P.M.B 25 Mubi, Adamawa State. Nigeria.

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Abstract

Glufosinate ammonium (GA) a non-selective herbicide, use for total vegetation control and as a desiccant to aid in crop harvesting, its herbicidal action involves inhibition of glutamine synthetase activity in plants which lead to the plants death. Glufosinate ammonium pollution poses a threat to the environment and the habitats in it due to it persistent and toxicity. Glufosinate ammonium causes endocrine disruption, cardiovascular disorder, respiratory disorder, soil infertility, affect microbial diversity and aquatic organisms and as well affects beneficial arthropods. This study aimed to review the microbial strategies of the biodegradation of glufosinate ammonium in agricultural soil for sustainable herbicides remediation. To conduct this review, databases such as Scopus, Web of Science, PubMed, and Google Scholar were searched to extract studies on the biodegradation methods of glufosinate ammonium from 2007 to 2025. Microbial laboratory experimental which involves isolation, characterization, optimization and degradation determination of the effects of incubation time, substrate concentration, inoculum size, pH, and temperature on the growth of the bacteria were spectrophotometrically assayed. The various bacteria strains identified based on this study, with high efficiency in biodegradation of glufosinate ammonium includes Pseudomonas citronellolis, Burkholderia sacchari, Serratia marcescens, Rhodococcus spp, and Bacillus tropius under optimized environmental conditions such as pH, inoculum size, substrate concentration, tempperature. The role of the isolated bacteria as degrader of glufosinate ammonium make it an important instrument for biodegradation of pollutants for sustainable agricultural practices.

Keywords: Biodegradation, Bacteria, Bioremediation, Environment, Glufosinate Ammonium, Herbicides

1. Introduction

The modern day agriculture involves the use of herbicides, thus raised significant concern due to their environmental pollution emission, reduce soil fertility, environmental sustainability and aquatic ecosystem ill-health which is reaching a worrying proportions worldwide, Environmental pollutants have various adverse health effects from early life, some of the harmful effects are perinatal disorders, infant mortality, respiratory disorders, allergy, malignancies, cardiovascular disorders, increase in stress oxidative, endothelial dysfunction, mental disorders, and various other harmful effects [1,2]. The extensive use of the herbicides leads to persistent hazardous residues in soils and water sources, which necessitates effective remediation strategies to mitigate environmental risks, glufosinate ammonium is a broad spectrum herbicide that control vegetation by inhibition of glutamine synthetase processes which is an enzyme that detoxify ammonia, aid in amino acid metabolism and nucleotide biosynthesis in plants [3]. Environmental pollution due to glufosinate ammonium residue cause public health concern and due to their exposure, affect soil fertility and microbial diversity. However, due to growing evidence of glufosinate ammonium toxicity for living organisms, environments (both soils and water bodies) and of its subsequent removal is becoming a topical issue. The only appropriate solution seems to be the use of microorganisms capable of degrading phosphonate xenobiotic into biologically safe compounds [1]. The European Union banned

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the agricultural use of glufosinate ammonium in 2018 [4]. A Study by Takano and Dayan (2020) indicated that the contact activity of glufosinate results from the accumulation of reactive oxygen species (ROS) and subsequent lipid peroxidation. Glufosinate disrupts both photorespiration and the light reactions of photosynthesis, leading to photo-reduction of molecular oxygen, which generates reactive oxygen species. Glufosinate efficacy depends on several factors related to the spraying conditions, temperature and humidity, and the target weeds. A good application technology and weather conditions can increase uptake levels, but the final concentration of glufosinate in leaves depends on metabolism rates. Another study by Narasimha (2022) indicated that Glufosinate ammonium is being used as broad-spectrum post emergence herbicide globally, and the use is expected to increase due to the development of herbicide tolerant crops [5]. It is a structural analog of glutamate and inhibits the glutamine synthetase enzyme, kill plants by ammonia accumulation and accumulation on reactive oxygen. Since glufosinate irreversibly inhibits glutamine synthetase, leading to intracellular accumulation of ammonia, hyperammonemia is considered one of the main mechanisms of glufosinate ammonium toxicity in humans. It is highly hazardous herbicide, owing to the fact that it can cause reproductive toxicity, neurotoxicity, and cardiovascular effects. It is also capable of causing damages to developing fetuses. Similarly, Zhou (2021) reported that glufosinate ammonium residues in aquatic systems break down into toxic byproducts, affecting fish and other aquatic organisms [6]. Microbial degradation of glufosinate ammonium has been explored as a sustainable approach to mitigate its environmental impact. Several bacterial species, including *Pseudomonas sp, Bacillus sp*, and *Streptomyces sp,* have been identified as potential glufosinate ammonium degraders [7].

2. Materials and Methods

This review was conducted using key terms of glufosinate ammonium and biodegradation of glufosinate ammonium. In this regard, databases including Scopus, Web of Science, PubMed, and Google Scholar along with related published books in this field were investigated. Considering the study aims, more detailed references with technical explanation and clarification on glufosinate ammonium biodegradation methods in soil were included; whereas, the unrelated articles and references were excluded. Some of the excluded articles were on other aspects of glufosinate ammonium, such as its removal or were published before year 2007. In addition, the articles published in languages other than English were excluded.

3. Results

3.1. GA: general action and bioactivity

The results of biodegradation of glufosinate ammonium studies are summarized in table 1. Previous glufosinate ammonium biodegradation studies identified different species of microbial capable of degrading glufosinate ammonium. The table 1 represents the microbial species, isolation environments, pollutants, and mechanisms of degradation. The microbial species are isolated based on their morphology and biochemical test from various glufosinate ammonium-contaminated environments.

S/N	Degrading strains	Source	Herbicide	Mechanisms	Reference(s)
1	*Pseudomonas citronellolis*	Soil	Glufosinate ammonium	Co-metabolism	Hsaio *et al.*, 2007
2	*Burkholderia sacchari*	Soil	Glufosinate ammonium	Co-metabolism	Hsaio *et al.*, 2007
3	*Serratia marcescens*	Soil	Glufosinate ammonium	Co-metabolism	Hsaio *et al.*, 2007
4	*Rhodococcus spp*	Soil	Glufosinate ammonium	Co-metabolism	Wang *et al.*, 2022
5	*Bacillus tropius*	Soil	Glyphosate	Co-metabolism	Fatima *et al.*, 2022
6	*Streptomyces hygroscopicus*	Soil	Glufosinate ammonium	Acetylation	Takayo and dayan *et al.*, 2020

Table 1: Microbial Degradation of Glufosinate Ammonium

3.2. Glufosinate ammonium chemistry and toxicity

Glufosinate ammonium, chemically known as ammonium (2RS)-2-amino-4-(methylphosphinato) butyric acid, with molecular formula of $C_5H_{15}N_20_4P$ and molecular weight of 198.16g/mol, is a non-selective, post-emergence herbicide that belongs to the organophosphate class (Copping and Duke, 2021). It was initially derived from phosphinothricin, a naturally occurring compound found in Streptomyces viridochromogenes, a type of soil-dwelling bacterium that produces antibiotics and herbicidal compounds [6]. Due to its broad-spectrum activity, glufosinate ammonium is widely used in agriculture to control weeds in various crops, including maize, soybean, cotton, and orchards. It is particularly effective in controlling weeds that have developed resistance to glyphosate and other herbicides [3,7]. Glufosinate ammonium is characterized by water solubility, making it prone to leaching into groundwater and contaminating aquatic environments. It exhibits persistence in soil, meaning that it does not break down immediately but remains active long enough to control weed growth.

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Its chemical stability varies depending on environmental conditions, as it degrades more rapidly under high temperatures and UV light exposure but remains stable in acidic conditions [15]. Figure 3 below show the structure of glufosinate ammonium.

The persistence and impact of glufosinate ammonium in soil and water have been studied in different agricultural settings. The half-life in water of glufosinate is expected to be less than 300 days. Found that glufosinate ammonium alters soil microbial communities, reducing beneficial bacteria involved in nitrogen cycling [3,8]. Similarly reported that glufosinate ammonium residues in aquatic systems break down into toxic byproducts, affecting fish and other aquatic organisms [6]. The EPA classifies the chemical (residue) as 'persistent' and 'mobile' based on its lack of degradation and ease of transport through soil. Residues can remain in frozen food for up to two years and the chemical is not easily destroyed by cooking the food item in boiling water. These findings highlight the need for effective biodegradation strategies.

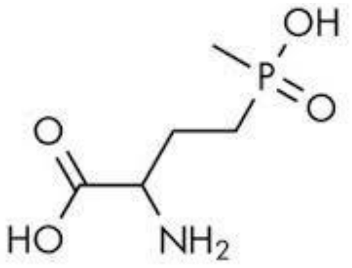

Figure 1: Chemical Structure of Glufosinate Ammonium

3.3. Mechanisms of action of glufosinate ammonium

figure 2 show the mechanisms of action of glufosinate ammonium where it exerts its herbicidal effect by inhibiting glutamine synthetase, a crucial enzyme responsible for several vital functions in plants, including ammonia detoxification, amino acid metabolism and nucleic acid biosynthesis. The inhibition of this enzyme disrupts nitrogen assimilation, leading to the accumulation of toxic levels of ammonia within plant cells. This buildup of ammonia interferes with cellular metabolism, causes membrane damage, and ultimately results in plant necrosis [7].

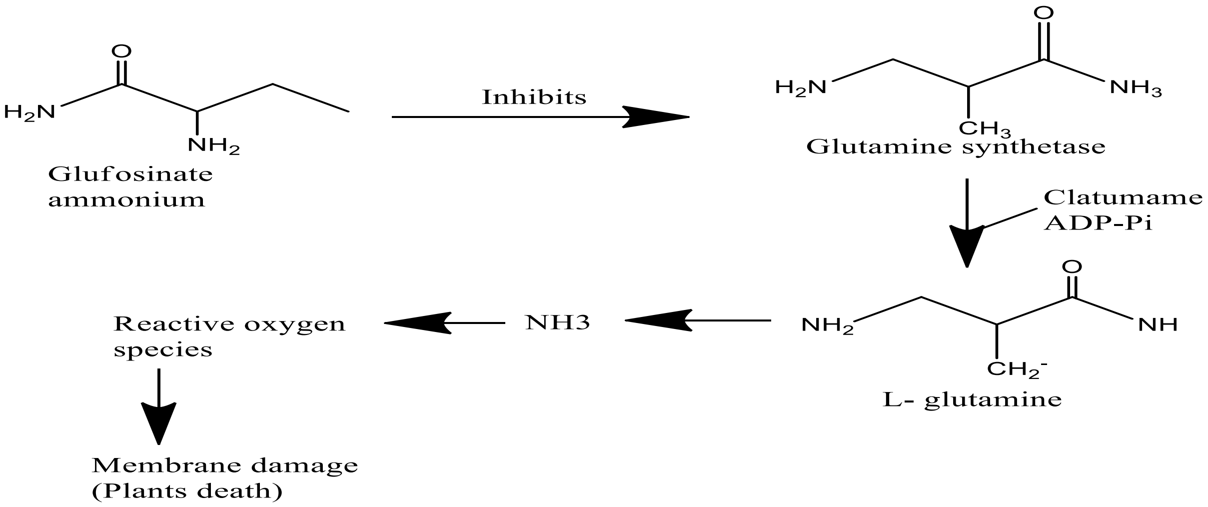

Figure 2: Mechanisms of action of Glufosinate ammonium

Figure 3 shows Mechanisms of degradation and microbial removal of glufosinate ammonium residues in soil, reported that microbial degradation is the primary route for glufosinate ammonium dissipation in soil [9,10]. Specific soil bacteria, such as Pseudomonas, and Bacillus species, utilize glufosinate ammonium as a source of carbon [11]. The degradation begins with deamination of glufosinate to form 3-methylphosphinico-propionic acid (MPP), which further broken down into 3-methylphosphinico-acetic acid (MPA) and ultimately to inorganic phosphate and CO_2. Pseudomonas species are known for their metabolic versatility. They degrade glufosinate primarily through oxidative deamination, a process in which the amino group of glufosinate is removed. Glufosinate ammonium → 3-methylphosphinico-propionic acid (MPP) → 3-methylphosphinico-acetic acid (MPA). These reactions involve enzymes like phosphinothricin acetyltransferase and aminotransferases, allowing the bacteria to assimilate nitrogen and phosphorus. Bacillus species degrade glufosinate by producing extracellular enzymes that catalyze the breakdown of carbon-nitrogen (C–N) and phosphorus-carbon (P–C) bonds, the bacteria secrete hydrolases and oxidoreductases that initiate the cleavage

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of the herbicide molecule, further utilize the metabolites (like MPP and MPA) as energy or nutrient sources [12]. Agrobacterium sp, utilize aminomethylphosphonic acid (AMPA)-like degradation pathways to transform glufosinate. They harbor C–P lyase systems, which break down the carbon–phosphorus bond—a key step in fully mineralizing the herbicide. Glufosinate is converted to MPP, then to MPA, and finally to phosphate, formate, and CO_2. [13]. 90% of the mechanism of action of glufosinate ammonium degrading strains were through co-metabolism with only about 10% through acetylation.

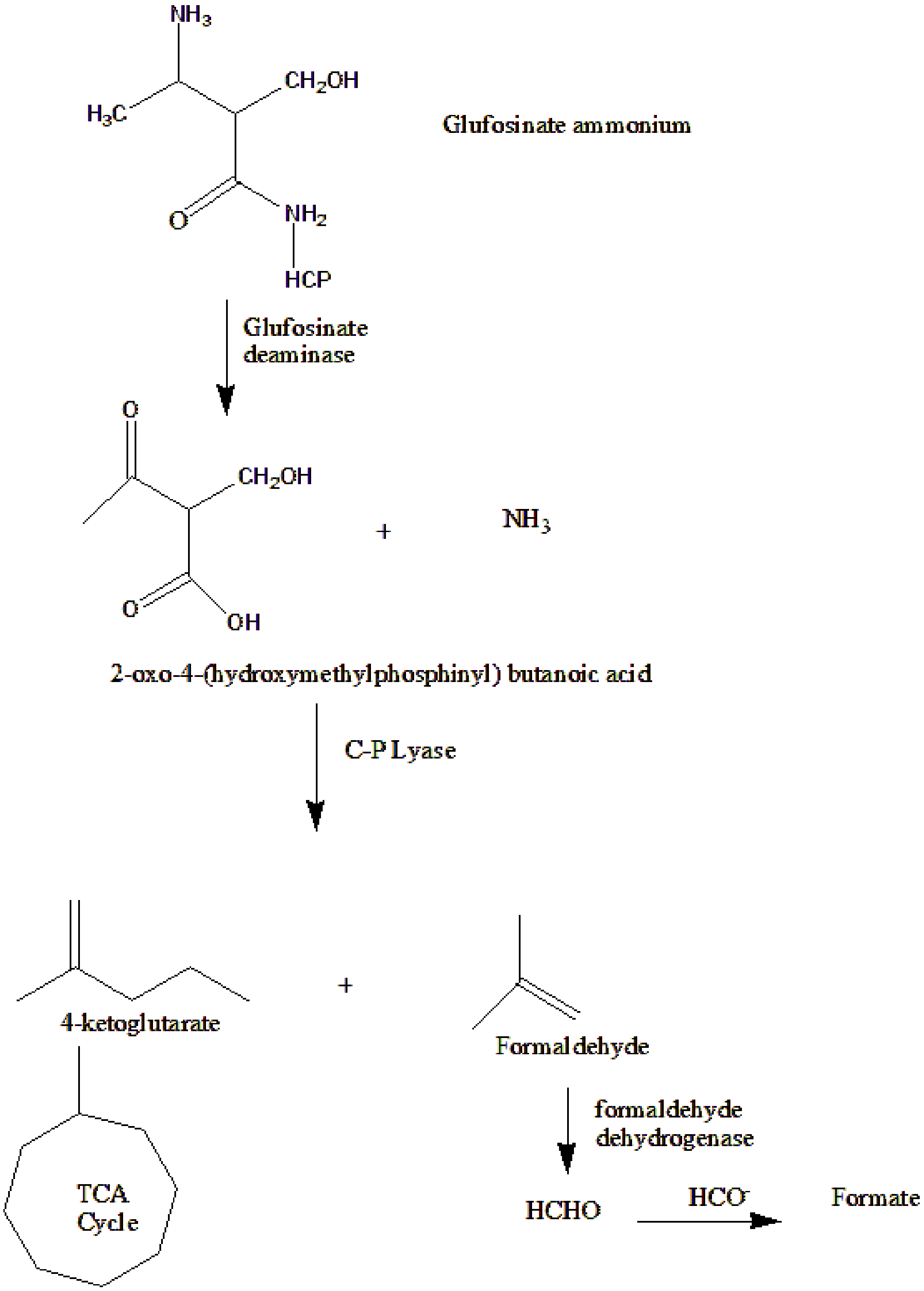

Figure 3: mechanisms of degradation of glufosinate ammonium residues by bacteria Future Perspective and Research

Even though research is in progress in understanding the microbial degradation of glufosinate ammonium in soil, several gaps remain which can be address through innovative and interdisciplinary research to ensure sustainable soil ecosystem health. These may involve.

Exploration and Engineering of Novel Microbial Strains

Future research should explore genetic engineering and synthetic biology approaches to enhance metabolic pathways responsible for degradation. example, engineer microbes to overexpress carbon-phosphorus (C–P) lyases or phosphinothricin acetyltransferase could improve mineralization efficiency under various environmental conditions, through metagenomics, CRISPR-based microbial editing [10].

Development of Microbial Consortia and Bioaugmentation Strategies

Future studies should develop microbial consortia that mimic natural soil ecosystems and function cooperatively to degrade glufosinate. Bio-augmentation strategies using such consortia can enhance the resilience and stability of biodegradation processes, especially in contaminated or depleted soils.

5. Conclusion

The biodegradation of glufosinate ammonium residues in agricultural soils is an aspect of sustainable herbicide management, particularly in light of its widespread use and potential environmental effects. This review has extracted bacteria strategies employed to degrade glufosinate ammonium, emphasizing the role of specific bacteria capable of utilizing the herbicide as a nitrogen or carbon source. These bacteria populations possess diverse enzymatic pathways such as phosphinothricin acetyltransferase, oxidoreductases, and hydrolases that contribute to the transformation and mineralization of glufosinate into less harmful compounds. the mechanisms of microbial degradation aids in mitigating the accumulation of herbicide residues and also aligns with the goals of sustainable agriculture by reducing dependence on physical or chemical remediation methods which are costly, unfriendly and may further disrupt soil ecosystems. these strategies depend significantly on environmental factors such as soil pH, temperature, moisture content, and the presence of co-substrates, all of which influence microbial activity and degradation efficiency [15-66].

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