Herbicide Formulations and their Importance

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ABSTRACT

Herbicide formulations are crucial for effective weed management, enhancing application efficiency, stability, and safety while minimizing environmental impact. With global food demand rising and weeds causing an average 34% yield loss, herbicides—accounting for 1,732.3 thousand metric tons of global pesticide consumption in 2023—play a key role in modern agriculture. Formulations such as emulsifiable concentrates (EC), water-dispersible granules (WDG), and microencapsulated herbicides (ME) improve herbicide performance, reduce drift, and enhance crop safety. Selection depends on factors like target weed species, application method, and environmental impact, with granular (G) and WDG formulations posing lower human exposure risks. However, challenges such as herbicide resistance, environmental contamination, regulatory restrictions, and volatility issues persist. Advanced research in controlled-release and eco-friendly formulations is crucial for sustainable weed management and future agricultural productivity.

INTRODUCTION

The global population is projected to reach 8.7 billion by 2033, leading to higher food demand and requiring effective weed control strategies. Weeds cause an average crop yield loss of 34% due to competition for light, water, and nutrients (Singh *et al*. 2022). Among pesticides, herbicides account for the highest global

consumption, reaching 1,732.3 thousand metric tons in 2023 (FAO 2023). They play a crucial role in modern agriculture by ensuring efficient weed management, enhancing yields, and improving crop quality (Paul *et al*. 2024).

Herbicides in their natural state may be solid, liquid, volatile, non-volatile, soluble, or insoluble. To ensure safe and effective field application, manufacturers formulate them by blending the active ingredient with solvents, surfactants, and stabilizers. A herbicide formulation is a specific mixture designed to enhance handling, application, stability, and effectiveness. Different formulation types, such as emulsifiable concentrates, wettable powders, and granules, influence application methods, mode of action, and environmental impact. The primary objectives of herbicide formulations include easy handling, enhanced weed-killing efficiency, and broader weed control. They also ensure uniform application of small herbicide amounts in the field and improve storage properties. The formulation process involves selecting suitable active ingredients, inert components, and adjuvants. Solvents dissolve the active ingredient for easier application, surfactants enhance spreading and wetting on plant surfaces, and adjuvants improve herbicide performance by increasing adhesion and efficacy.

Why Are Formulations Important?

Formulations play a vital role in herbicide application by ensuring proper delivery, enhancing efficiency, improving safety and increasing shelf life. They prevent losses due to drift or evaporation, as seen in Emulsifiable Concentrate (EC) formulations, which ensure even glyphosate distribution for effective weed control. Formulations also improve active ingredient performance, such as surfactants in paraquat formulations that enhance leaf penetration for better broadleaf weed control. Additionally, they enhance safety by reducing toxicity risks, as granular atrazine formulations lower exposure compared to liquids.

Classification of Herbicide Formulations

Herbicide formulations are categorized into dry, liquid, and specialized formulations.

Dry formulations

Granular (G) herbicide formulations are dry, ready-to-use products with large particles applied directly to the soil without water. Containing 2-15% active ingredient, they release herbicide gradually, ensuring sustained weed control. Examples include Butachlor 5% GR, 2,4-DEE, and Alachlor. Pellet (P) herbicides are similar but have a higher active ingredient concentration (10-20%) mixed with an inert carrier, providing controlled soil treatment while enhancing applicator safety. An example is Tebuthiuron (Spike 20 P). Wettable Powder (WP or W) is a finely ground dry formulation that must be mixed with water before application. It does not dissolve but remains suspended, requiring constant agitation. Containing 15-80% active ingredient, examples include Atrazine, Simazine, and Isoproturon. Soluble Powder (SP) formulations contain over 50% active ingredient and dissolve completely in water, forming a true solution. They pose minimal equipment wear but present inhalation risks. Common examples include 2,4-D Na/K, TCA, and Endothal. Water Dispersible Granules (WDG) or Dry Flowables (DF) are granulated formulations that disperse rapidly in water, forming stable suspensions similar to WP but with easier handling and minimal dust formation. These formulations, containing up to 90% active ingredient, improve application efficiency while reducing clogging in spray equipment. Their composition includes dispersing agents (5–15%), wetting agents (1–3%), and binders (0–2%). Examples include Diuron 80, Escort, Glufosinate-ammonium 88% WSG/WDG, and Carfentrazone 40% DF,

commonly used for effective weed management.

Liquid formulations

Solution herbicides contain active ingredients that dissolve completely in water without settling or separating, ensuring even application. Wettable Soluble Concentrates form a true solution when mixed with water, often incorporating amine or mineral salts for enhanced solubility. These nonvolatile formulations require no agitation and typically contain 2 to 6 pounds of active ingredient per gallon. Examples include Garlon 3A, Krenite, and Roundup Pro. Emulsifiable Concentrates (EC) are oil-based formulations that create a milky emulsion when mixed with water, requiring agitation to prevent separation. Primarily used for post-emergence weed control, they offer effective application but may cause phytotoxicity, skin irritation, and are flammable. Examples include Pendimethalin and Alachlor. Flowable or Aqueous Suspensions (F, L, or AS) consist of finely ground solid herbicide particles suspended in a liquid carrier. Similar to wettable powders (WP), they form a stable suspension when mixed with water, making them ideal for water-insoluble herbicides. These formulations require moderate agitation and rarely clog spray nozzles, with a high active ingredient concentration (typically 4 pounds or more per gallon). An example is Diuron 4L.

Specialized formulations

Microencapsulated Herbicides (ME) encase the active ingredient in polymer-coated capsules, enabling gradual release over time while reducing drift and phytotoxicity. These formulations protect herbicides from volatilization, degradation, and leaching, enhancing their stability and effectiveness. However, they may have higher costs and slower action. An example is encapsulated pendimethalin, which provides extended weed suppression in rice and maize. Controlled-Release Herbicides (CR) slowly release the active ingredient based on environmental triggers such as moisture, microbial activity, or chemical conditions, ensuring prolonged weed control while minimizing contamination. These formulations reduce runoff and leaching, extend control duration, lower re-application frequency, and remain effective even in adverse weather conditions. An example is a slow-release atrazine formulation.

Newer Trends in Formulations

New formulation technologies aim to improve application efficiency, safety, and environmental impact while reducing costs. Advancements include suspension concentrates, microemulsions, granules, gels, and controlled-release formulations like ZC, ZE, and ZW. These innovations make herbicides more effective, safer, and easier to handle.

Suspension Concentrates (SC) are water-based formulations with 40-70% micronized active pesticide, ensuring stability, low viscosity, effective wetting, and reduced sedimentation. Thickeners like bentonite and xanthan gum prevent nozzle clogging, offering dust-free handling, low toxicity, better bio-efficacy, and improved adhesion. Microencapsulated Suspensions (CS) enclose active ingredients in capsules for controlled release, reducing toxicity, phytotoxicity, and volatilization while extending activity and minimizing environmental impact (e.g., Pendimethalin 38.7% CS). Concentrated Emulsions (EW) are oil-based, safer than emulsifiable concentrates (EC), non-flammable, and environmentally friendly, with smectite clay and xanthan gum stabilizing the emulsion (e.g., Butachlor 50% EW, Pretilachlor 37% EW). Microemulsions (ME) are thermodynamically stable water-based formulations with ultra-fine pesticide particles (~0.01 microns), enhancing transport,

absorption, stability, and bioavailability for superior weed control. Oil Dispersion (OD) is a water-free formulation suitable for water-sensitive active ingredients but prone to sedimentation. Concentrated Aqueous Emulsions (EW) are a safer EC alternative, using water as the continuous phase to reduce phytotoxicity and handling risks, stabilized by polymeric surfactants (e.g., Carfentrazone ethyl 10.43% + Glyphosate 30.82% EW, Butachlor 50% EW). Aqueous Suspo-emulsions (SE) combine SC and EW, containing solid particles and fine globules in a stable dispersion, allowing two active ingredients with different properties in a single formulation.

Multi-character liquid formulations: Mixed formulations

ZC formulation is a blend of Capsule Suspension (CS) and Suspension Concentrate (SC), incorporating microcapsules and solid particles with active ingredients. It eliminates tank mixing issues, enhances pest control with fewer applications, and offers dust-free, non-flammable, and water-miscible properties for broad-spectrum efficacy. An example is Pendimethalin 38.4% + Pyrazosulfuron ethyl 0.85% ZC. ZE formulation combines Capsule Suspension (CS) and Suspo-emulsion (SE), integrating microcapsules, solid particles, and emulsion droplets to improve compatibility and pest control efficiency. This formulation allows three active ingredients in different forms (capsule, suspension, and emulsion) within a single product, removing the need for tank mixing. ZW formulation merges Capsule Suspension (CS) and Concentrated Aqueous Emulsion (EW), containing microcapsules and emulsion droplets. It enhances residual activity, reduces toxicity, and stabilizes the formulation for improved performance while eliminating tank mixing requirements.

Selection Criteria for Herbicide Formulations

The choice of formulation depends on several factors, including target weed species, application method, environmental impact, crop safety, and herbicide mode of action. For example, EC formulations penetrate leaf surfaces quickly, making them effective against broadleaf weeds, while WDG formulations are better for grassy weeds. Rainfastness and weather conditions also affect formulation stability, with SC and EW formulations being more resistant to washing away than WP. Mixing compatibility matters for ease of use, as SL and SC formulations mix well with other pesticides, whereas WP may form clumps. Additionally, toxicity and human safety considerations favor granular (G) and WDG formulations, which pose lower exposure risks than EC formulations.

Challenges and Limitations

Despite their benefits, herbicide formulations face several challenges. Herbicide resistance is a growing problem, with repeated applications leading to resistant weed populations (e.g., glyphosate-resistant *Amaranthus*). Environmental concerns arise due to contamination of soil, water, and non-target organisms, as seen with atrazine runoff causing algal blooms. Drift and volatility of some formulations, such as dicamba, result in unintended crop damage. High development costs, strict regulatory restrictions, and storage stability issues further complicate formulation use.

CONCLUSION

Herbicide formulations are essential for modern agriculture, ensuring effective weed control, improved yields, and reduced labor. While challenges like resistance, environmental concerns, and regulatory restrictions persist, ongoing research in advanced formulations and sustainable

practices will shape the future of herbicide application. A balanced approach integrating technology, eco-friendly solutions, and precise application techniques is crucial for sustainable weed management.

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