RP Current Trends In Agriculture And Environmental Sciences
Vol. 2, No. 2 (April – June 2023) pp. 14–21
e-ISSN: 2583-6293

RESEARCH PLATEAU PUBLISHERS

Cite this article: S. Balda, U. Kamboj, Herbicide – resistant crops: Challenges, innovations and environmental concerns, *RP Cur. Tr. Agri. Env. Sci.* **2** (2023) 14–21.

Review Article

Herbicide – resistant crops: Challenges, innovations, and environmental concerns

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ARTICLE HISTORY
Received: 10 March 2023
Revised: 2 June 2023
Accepted: 3 June 2023
Published online: 4 June 2023

KEYWORDS
Cropping systems; Food security; Glyphosate; Herbicide-resistant crops; Integrated weed management; Weed resistance.

ABSTRACT
Weed management is crucial for crop production, with herbicides commonly used to maximize yields. The rise of herbicide-resistant crops, especially those resistant to glyphosate, dicamba(3,6-dichloro-2-methoxybenzoic acid) and 2,4-D (2,4-dichlorophenoxyacetic acid), has changed weed management practices. The continuous dependence on glyphosate in earlier years has led to present problematic situation of weed resistance, emphasizing the need for careful stewardship of new technologies. Emerging herbicide-resistant traits in soybeans, combined with existing traits, offer effective tools against resistant weeds. The widespread adoption of herbicides in the mid 20th century, fueled by factors such as cost-effectiveness and labor reduction, saw a significant evolution with the introduction of genetically-modified glyphosate-resistant crops in the late 20th century. Glyphosate, a widely embraced herbicide due to its efficacy and selectivity, became the most extensively used herbicide globally. However, the rapid and extensive application of Glyphosate led to the emergence of glyphosate-resistant weeds, posing challenges in agronomic cropping systems. By continuous application of herbicides with dissimilar sites of action, preferably in combinations or rotations, can slow resistance evolution. Integrated Weed Management (IWM) is crucial for long-term success, enhancing ecological complexity in cropping systems and addressing challenges in herbicide-resistant weed management for global food security. Despite evidence supporting alternative tactics for enhanced profitability and weed resistance management, growers often resist diversifying due to perceived risks and economic concerns. However, the potential for unintended off-target movement and harm to nearby sensitive crops raise environmental concerns. The review concludes by highlighting the need for sustainable weed management practices, considering the ecological impact of emerging herbicide-resistant crop traits and changes in herbicide application practices on biodiversity.

1. Introduction

The swift and extensive acceptance of herbicides in the late 1940s and early 1950s can be attributed to various factors, including a favorable cost/benefit ratio, convenience, diminished labor requirements, fast application methods, rapid plant elimination, and high selectivity between crops and weeds, all contributing to their overall effectiveness [1]. The adoption of genetically-modified glyphosate-resistant crops allows farmers to apply glyphosate post-emergence in a broad manner for weed control in crops such as soybean (*Glycine max*), maize (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), canola (*Brassica napus* L.), sugar beet (*Beta vulgaris* L.) and alfalfa (*Medicago sativa* L.), effectively managing weeds without harming the crops [2]. Glyphosate-resistant crops being widely accessible have elevated glyphosate to become the most extensively utilized herbicide globally. Nonetheless, the widespread application of glyphosate has resulted in numerous instances of weed resistance reported across various countries [3]. The appearance resistance of weed towards glyphosate has presented fresh objections in numerous crop production practices, prompting the development of new technologies to address this aversion. Genetic engineering-based herbicide-intransigent traits, such as 2,4-D and dicamba-resistant soybeans, represent advancements that significantly enhance weed management in agricultural crops [4], while both germicides have the capability to cause harm to nearby tactful broadleaf plants due to off-target movement [5, 6]. The broad acceptance of dicamba-tolerant traits in soybean and cotton, alongside the introduction of novel dicamba spray formulations for weed management, has resulted in the widespread application of dicamba-based herbicides. Regrettably, this increased reliance on dicamba has coincided with a notable uptick in instances of non-target crop damage. The approval and integration of these technologies emphasize the imperative for thoughtful examination of the potential risks and unintended repercussions linked to the use of such herbicides in agricultural settings [5].This review offers a summary of the dependence on herbicide-resistant crops, the weed resistance challenges stemming from their inadequate management, the development of latest herbicide character methodologies aimed at improving weed resistance management, and certain challenges arising from the practical application of these innovations in the field.

2. Leaningon herbicide resistant plants

The current challenges with weed resistance in numerous agronomic cropping systems can be attributed directly to the extensive use of glyphosate. The introduction of glyphosate-resistant agronomic plants has revolutionized weed management for most growers, providing a highly effective, user-friendly, cost-regulated, and relatively safe alternative [5]. The emergence of crops endowed with combined resistance to glyphosate and synthetic auxin herbicides, known as stacked herbicide resistance, presents a challenge to the sustainability of weed management. This development increases the likelihood of a more severe proliferation of resistant weed populations, and the extended utilization of herbicides raises concerns about potential adverse impacts on environmental quality [7]. The technology proves to be both efficient as well as user-friendly, prompting farmers to frequently opt for exclusive cultivation of glyphosate-resistant cultivars and consistent application of glyphosate herbicide in the same fields, endlessly [8]. As a result, numerous soybean growers depended solely on glyphosate for weed control, resulting in a decreased utilization of alternative herbicide options [9]. Numerous growers refraining from applying soil residual herbicides directly resulted in the need for quite a few standing crop implementations of glyphosate, sometimes reaching equivalent to four or more per growing season [5]. Moreover, the schedule of averted applications underwent a shift, occurring either at planting or several weeks after planting. This approach offered agriculturist the authorization of controlling various species, both winter and summer annuals, with a single application. Furthermore, delaying the post-emergence application of glyphosate enabled growers to manage weeds that would emerge after the initial burn down, although there was a potential for weeds to reach a height of 29.9 inch if the post-advent supplication was postponed [9]. This led to the extensive overutilization and improper application of the herbicide in glyphosate-resistant crops. Despite the generally perceived success of glyphosate-resistant crops, the emergence of weeds resistant to glyphosate occurred more rapidly and extensively than anticipated.

Glyphosate resistance is the predominant trait among herbicide-resistant (HR) crops, in spite of the fact that various other crop traits offer resistance to diverse herbicides. Crops such as maize, alfalfa, canola, soybean, cotton, potato, sugar beet, and wheat have been engineered for glyphosate resistance, primarily by incorporating the cp4 epsps gene (*Agrobacterium tumefaciens* strain CP4). Besides, resistance to glyphosate in other crops involves the utilization of genes such as gat4621 (*Bacillus licheniformis*), goxv247 (*Orchobactrumanthropi* strain LBAA), mepsps or 2mepsps (*Zea mays*). Genetic modification for resistance to glufosinate has been applied to canola, chicory (*Chicorium intybus* L.), maize, cotton, rice, soybean, and sugar beet, incorporating the bar (*Streptomyces hygroscopicus*) and pat (*S. viridochromogenes*) genes [10]. Growers have traditionally favored glyphosate-resistant crops for various reasons. These include securing market share ahead of the arrival of glufosinate-resistant crops, as well as benefiting from lower costs and greater flexibility compared to the latter. For instance, given that glufosinate is a contact herbicide requiring thorough coverage, a higher bearer volume (140 to 187 L ha^{-1}) is needed for its stirring in contrast to glyphosate (94 L ha^{-1}).Moreover, the recommended weed height for glufosinate application is under 10 cm. Glufosinate controls 110 fewer species, has a limited application window up to R1 in soybeans (compared to R3 for glyphosate), and requires a rain fast phase of 4 hours, in contrast to some formulations of glyphosate with a 30-minute rain fast period. Furthermore, glyphosate offers superior control of perennials compared to glufosinate. This provides an upper hand in zero tillage agronomic practices, where the absence of tillage may otherwise facilitate the establishment of perennials [11, 12]. Shortly after its establishment, the acquisition of glyphosate-resistant cotton surpassed the utilization of genetically-enhanced bromoxynil-resistant cotton. Genetic modification has facilitated the creation of crops resistant to acetolactate synthase-inhibiting herbicides, exemplified by corn. The sethoxydim-resistant maize hybrid exhibited significant tolerance to both sethoxydim and other acetyl CoA carboxylase (ACCase) inhibitors, including fluazifop-P, quizalofop-P, and clethodim. Among herbicides that inhibit ACCase, the sethoxydim-resistant maize displayed the least cross-resistance, particularly to clethodim. In 1996, successful suppression of volunteer sethoxydim-resistant maize and prevention of soybean yield loss were achieved exclusively with AC 299, 263 and the combination of imazethapyr plus imazaquin. Furthermore, attributes deriving from gametoclonal variation and conventional breeding incorporate sethoxydim-resistant maize [13], imidazolinone-resistant maize, wheat, rice, canola, and sunflower [14] as well as nicosulfuron-resistant sorghum [15].

The next generation of herbicide-resistant crops has been genetically modified to exhibit opposition to supplementary weedicide categories and vigorous constituents. Intransigent features to glufosinate and glyphosate are now being amalgamated along with resistances to acetyl CoA carboxylase inhibitors (from the chemical family of aryloxyphenoxypropionates or FOPs), plant growth regulators (involving active ingredients such as dicamba and 2,4-D), acetolactate synthase inhibitors (falling into the elemental groups of sulfonureas and imidazolinones), and hydroxyphenylpyruvate dioxygenase inhibitors (involving active ingredients like isoxaflutole and mesotrione). The combination of these stacked traits has the potential to impede the evolution of resistance if managed carefully and under specific circumstances. To achieve this, the exogenous genesought topick the alike weed breeds receptive to more than two piled up weedicide active ingredients. It is crucial that the addressed weeds are seldom cross-reluctant to the weedicides, and both herbicides necessarily be used with comparably equivalent surplus outcomes [16]. Nevertheless, this marks the inaugural occasion where all attributes acquainted to the merchandise will have pre-existing resistant weed species somewhere in the United States [3]. The emergence of germicide-resistant plants aligns besides the anticipation among growers that new technology will address herbicide resistance challenges [17]. Effective management of these novel trait technologies necessitates proper stewardship, encompassing the implementation of an unsegregated weed control plannings. This involves deploying mechanical, cultural, chemical and biological methods at relevant schedule [18]. Moreover, incorporating ideal supervision operations, which may perhaps encompass Integrated Weed Management strategies, is crucial to decelerate the advancement and dissemination of weedicide-resistant plants [19]. Research has recorded growers' hesitancy to adopt natural approaches for weed management, primarily attributed to concerns regarding satisfaction, convolution, and price [20] where there is a constant likelihood of recurrent past blunder done in the governance of glyphosate-resistant plants.

In regions where intensive agricultural practices are widespread, the past decade has seen notable progress and shifts in weed management strategies. These encompass heightened initiatives by the agrichemical industry to discover new herbicides, the cultivation of crops with combined herbicide-resistant traits, a growing preference for pre-emergence over post-emergence herbicides, the development of crop cultivars designed to outcompete weeds, the expansion of practices targeting weed seed control during harvest, and advancements in precision weed management techniques. The overarching theme uniting these developments is a strategic focus on mitigating the presence of viable weed seeds in the soil seed bank, with the goal of maintaining low weed seed banks. This strategic approach aims to reduce the proliferation of weed populations, restrain the development of resistance to additional herbicidal sites of action, and prevent the spread of problematic weed species [21]. Studies indicate equivalent utilization of after sowing and pre-onset herbicides has risen from 25% to 70% in area under soybean production in the United States between 2000 and 2015 [22]. In an integrated weed management program, incorporating before onset, soil-employed weedicides are crucial, as it can potentially impede the shift towards post-emergence products by offering early weed control. The development of tolerance to pre-onset weedicides had not occurred as rapidly as with after sowing selection pressure together with the application of soil-administered weedicide combinations could additionally impede the progression of resistance evolution in pre-onset usage [23]. Failure to implement rotations or relying on simplified rotations of soil-applied herbicides may lead to the evolution of resistance [24]. As the pre-emergence herbicide rate diminishes in the soil over time, decreasing concentrations from single Sites of Action (SOA) applications may enable the emergence of herbicide-resistant weeds [25]. Hence, incorporating additional strategies alongside herbicides for before and after sowing remains crucial for resistance administration. Based on cumulative earlier experiences in the nomination for weedicide-resistant plants, nowadays it is clear that the development of weedicide resistance is unavoidable specially when herbicides serve as the sole solution for unwanted plant management [26]. Upon the evolution of herbicide resistance, these unaffected genotypes can disseminate with the help of spontaneous or automatic mechanisms, potentially affecting management practices beyond herbicide-tolerant cropping systems.

3. Herbicide resistance

The excessive dependence on glyphosate herbicide within agronomic cropping systems that are resistant to glyphosate has resulted in the development of weeds that are resistant to this specific herbicide [2]. Regardless of the evolving environment of herbicide-resistant plants attributes, lately, the market was majorly influenced by single-trait glyphosate-resistant plants. From 2009 to 2011, herbicide usage in the United States witnessed a surge of 239 million kg, primarily attributed to non-herbicide-resistant land with glyphosate being the major contributor to this rise [27]. Numerous weed scientists foresaw the emergence of glyphosate-resistant weed hybrids as a consequence of excessive glyphosate application, mainly relying on this herbicide as the sole method for weed management [28, 29]. Nearly 300 instances of glyphosate-resistant weeds have been verified, encompassing close to 40 species across 28 countries [3]. The extensive commercialization of glyphosate-resistant crops, encompassing canola, cotton, maize, and soybean, has demonstrated a lower environmental impact of glyphosate on soil, water, and air contamination compared to the herbicides they replaced. Currently, these crops exhibit no identified risks concerning food or feed safety, or nutritional value. Moreover, they have played a pivotal role in advancing environmentally friendly reduced- or no-tillage agriculture. Nonetheless, challenges arise from shifts in weed species towards those more resilient to glyphosate, and the emergence of three weed species exhibiting glyphosate resistance in fields with these crops. Additional concerns include the potential for these crops to become volunteer crops and the identification of glyphosate resistance transgenes in non-transgenic canola fields [30]. Despite assertions of reduced pesticide use with genetically-engineered crops, the rise of glyphosate-resistant weeds in herbicide-resistant systems has resulted in substantial increases in both the quantity and volume of herbicides applied. The potential approval of new genetically engineered crops tolerant of 2,4-D raises concerns about a further 50% surge in herbicide usage. This escalation in herbicide application on herbicide-resistant hectares surpasses the reduction in insecticide use on Bt crops over the past 16 years and is expected to endure into the foreseeable future [27]. Furthermore, it is believed that the costs linked to the control of glyphosate-resistant weeds have increased by 50% to 100% [31].

The instantaneous onset of glyphosate-resistant weed plants emphasize that herbicide-resistant plants are reliable only when consolidated into even more diverse and environmentally intended weed control systems [7]. While existing weed management systems relying on glyphosate are under threat, as indicated by the rapid development of resistance in weed populations, glyphosate has not entirely lost its utility. It still proves effective in controlling a larger variety of weeds compared to most other herbicides [5]. With the transformation of glyphosate-resistant weed plants propounding a future harm to the progressing victory and sustainability of plants resistant to glyphosate applications, new technologies have been devised to address and manage these weed species resistant to glyphosate. These are recently developed mutagenic crops that manifest resistance to currently available herbicide vigorous constituents, either already introduced to the field or presently in the expansion stage (2,4-D, dicamba, isoxaflutole, mesotrione).Although these may provide partial solutions to the issue of widespread resistances and populations resistant to multiple herbicides, resistances to these chemical approaches are already observed in the United States [3]. As an illustration, there are globally 17 distinct instances of herbicide resistance to dicamba; among these, nine instances involve the similar breeds, *Bassia scoparia* (L.) A. J. Scott (also known as *Kochia scoparia* (L.) Schrad.), that serves as a key driver weed influencing management decisions in certain US regions. Additionally, between 2009 and 2018, two inhabitants of *A. tuberculatus* (in Illinois and Nebraska) and two inhabitants of *A. palmeri* (in Kansas) have been recognized as resistant to 2,4-D. With the exception of one population, all these populations manifesting resistance to several other active components, which includes ALS-inhibiting herbicides, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting weedicides such as mesotrione, as well as the operative components atrazine (a photosystem II-inhibiting herbicide) and glyphosate. In Iowa, there exists a singular instance of *A. tuberculatus* resistant to isoxaflutole, and this population also demonstrates resistance to ALS-inhibiting weedicides, atrazine, glyphosate, and mesotrione [3]. Although these instances are not prevalent examples of aversion, they indicate the potential for the evolution of resistance under heightened selection pressure.

Instances of herbicide resistance can be categorized as either target-site resistance or non-target-site resistance (NTSR).Target-site resistance (TSR) mechanisms encompass mutations in the genetic code related to an herbicide binding site or the excessive production of the targeted enzyme. Plants can also develop the capacity for metabolic resistance, enabling them to disinfectun familiar complexes, inclusive of weedicides. Metabolic resistance falls under the category of non-target-site resistance (NTSR), akin to decrease dengrossment or translocation, or weedicide sequestration. In this resistance mechanism, the weedicide fails to make it to the target location in a concentration appropriate to induce plant death. The rapid development of non-target-site resistance (NTSR) has been linked to the utilization of herbicide rates below the recommended levels. Research indicates that the evolution of target-site resistance can occur at a relatively swift pace under conditions of intense selection pressure, contingent upon the mutation rate of alleles imparting resistance [32].

In case the mutation rate stands at 5 individuals per one billion, it would require only 4000 plants, each yielding 250,000 seeds, to generate 5 resistant individuals [33, 34]. Anticipations suggest that should the evolution of weedicide resistance persist, coupled with the absence of new operations of proceedings, farmers will lack viable herbicide options upto year 2050 [35]. For around three decades, spanning until the 1980s, a new mechanism of action was introduced approximately every 2.5 to 3 years. Nevertheless, no updated mechanism of actions for crop production systems from the 1980s [36]. The development of aversion in weeds, such as mesotrione resistant *A. palmeri* to HPPD inhibiting herbicides and 2,4-D resistant A. *tuberculatus* to plant growth regulators, has been associated with non-target site resistance (NTSR). In this context, weeds exhibit the capacity to swiftly breakdownweedicides in operations that involve, glucosyl transferases, glutathione S-transferases, cytochrome P450 monooxygenases, and other enzyme systems like aryl acylamidase [15, 37, 38]. Adding complexity, populations resistant to herbicides may comprise a mixture of both target site resistance (TSR) and non-target site resistance [38]. The mechanisms associated with metabolic resistance have the potential to consult cross-resistance to weedicides that are still not in existence. Earlier research has primarily concentrated on target site resistance (TSR) mechanisms, and investigators might not have actively sought non-target site resistance (NTSR) mechanisms in weedicide-resistant inhabitants, especially if TSR operations were identified beforehand. The use of herbicide site of action tank mixtures constitutes a fundamental strategy for enhancing the diversity of weed management programs [39]. There is a forecasted decrease in the efficacy of tank mixes and rotations when dealing with non-target site resistance (NTSR), as communicated by Tranel. To illustrate, the rotational use of HPPD-inhibiting and plant growth regulator (PGR) herbicides could theoretically promote the selection of a detoxifying cytochrome P450 monooxygenase, potentially resulting in cross-resistance [40]. Hence, the presence of non-target site resistance holds the capacity to alter existing agronomic practices.

Despite mounting evidence that alternative tactics can enhance profitability and address weed resistance problems, numerous growers remain hesitant to diversify weed management practices due to the perception that these alternatives may be less cost-effective [41, 20]. The prevailing economic conditions in the US do not favor the acquisition of substitute herb administered operations by growers, primarily due to perceived risks associated with these tactics. The adoption rate may improve if there are financial and social incentives to encourage the adoption of varied weed control procedures, like Integrated Weed Management (IWM) outlook [17]. Grower networks, functioning at appropriate geographic scales, have the potential to promote proactive changes by facilitating the exchange of knowledge and equipment [42, 43]. Integrated weed management necessitates in-depth, intricate understanding of weed biology and ecology. This understanding is crucial for assessing the influence of management practices on seed reserves, implementing different weed control operations, determining the critical phase of weed intrusion, and creating ideal circumstances for the plant to enhance its contention [44]. Crop cultivars with strong weed competitiveness are frequently advocated as integral to an IWM strategy. This emphasis on weed-competitive cultivars is increasingly becoming a focal point in plant breeding initiatives, especially as plant attributes which enhance weed contention are identified [21]. Moreover, understanding mechanical practices like reduced tillage or yield out weed seed destruction, along with familiarity with traditional methods like diverse plant sequencing along with utilization of cover crops, proves precious in integrated weed management practices. Normally, when integrated weed management is implemented, it tends to be more reactive than proactive in its proposition towards control of weed species. Typically, there is an emphasis on varying weed plants handling primarily by the use of herbicide site of action mixtures [45]. Although mixtures can decelerate the evolution of target site resistance, they might enhance the selection for non-target site resistance, potentially resulting in cross-resistance to various sites of action groups [38].

4. Emerging herbicide trait technologies and evolving environmental concerns

Novel genetically modified varieties of soybean, cotton, maize, and canola, featuring resistance to additional weedicide formulations such as dicamba and 2,4-D in soybean, are being presented as a remedy for glyphosate-resistant weeds [7], however, there could be inherent difficulties in employing these emerging crop trait technologies. In cropping systems grappling with the prevalence of glyphosate-resistant weed species, combinations of isoxaflutole, mesotrione, glufosinate, dicamba, and 2,4-D have the potential to serve as an effective weed management tool [4, 33, 46]. Nevertheless, there is a possibility of unintended movement to non-target areas, which could lead to harm to nearby, susceptible broadleaf plants. Despite reports of damage from reduced rates or parallel accumulation rates of various weedicides in numerous plants, the drift of dicamba and 2,4-D is particularly alarming due to the significant potential for crop injury [47]. The impact of these Plant Growth Regulator (PGR) herbicides is readily identifiable through symptoms like leaf cupping, crinkling, and/or epinasty. Even at minimal herbicide rates, susceptible plants may exhibit signs of injury [48]. Soybean has been found damaged as per records in the previous research at the smallest published non-zero rate of 0.03 g/ha [49]. Although negligible amounts of Plant Growth Regulator (PGR) herbicides might not lead to yield losses in soybeans, chemical intrusion is against the law which could result in other unintended repercussions [50]. Soybeans exhibit the highest susceptibility among the tested species in response to dicamba, making them the designated benchmark for dicamba shift researches. The susceptibility benchmarks established with soybeans may not accurately represent the susceptibility of vernacular or uncultivated species, as these crops can exhibit remarkable variability in their reaction to dicamba owing to natural diversity. Although soybeans can burn down vapor and particle accumulation levels of 2,4-D [51], another crop plants, such as tomato (*Lycopersicon esculentum* Mill.), may not possess the same capability. In addition to vulnerable crop production, areas near herbicide-treated agronomic fields often feature the cultivation of fruit and vegetable crops, vineyards, orchards and homeowner gardens/landscapes. These position raise concerns regarding off-target movement, given their general high sensitivity to 2,4-D and dicamba [52].

The chemical compositions of weedicides vary in their potential for off-target movement, and new compositions designed for utilization in herbicide-resistant plants have been created to minimize volatility. Two approved forms of dicamba for use in HR crops include Dicamba DGA salt (diglycolamine salt of 3,6-dichloro-2-methoxybenzoic acid) with VaporGrip® technology and dicamba BAPMA salt (N, N-Bis-(3-aminopropyl) methylamine salt of 3,6-dichloro-2-methoxybenzoic acid). Notably, dicamba acid is highly volatile, exhibiting a vapor pressure of 4.32×10^{-5} mm Hg [53]. Recent formulations involve linking a larger, heavier salt to dicamba, resulting in a lower rate of volatilization compared to the older form of dicamba, DMA salt (dimethylamine salt of 3,6-dichloro-2-methoxybenzoic acid). In ongoing herbicide volatility studies, a choline salt formulation of dicamba is currently being employed however, there have been no announcements regarding plans to introduce this non-volatile formulation to the market. The herbicide 2,4-D has underwent a change in its chemical composition for its latest application in herbicide-resistant plant. In ancient times, chemical composition of amines or ester which was even more volatile more volatile was employed. The present formulation designed for herbicide-resistant crops involves the choline salt of 2,4-D (ethanaminium, 2-hydroxy-N, N, N-trimethyl-, 2-(2,4-dichlorophenoxy) acetic acid hydroxide). With a vapor pressure of 1.4×10^{-7} at 25°C, it is deemed non-volatile, comparable to 2,4-D dimethylamine (vapor pressure 1.0×10^{-9}) and significantly less volatile than the 2-ethylhexyl ester of 2,4-D (vapor pressure $2.92 \times 10^{-4)}$ [54].

Under favorable environmental conditions for particle and vapor drift, herbicides applied to crops have the potential to drift off-target, leading to potential injury to nearby agronomic or horticultural crops. Reducing dicamba volatility in soybeans can be addressed through environmental adjustments, such as lowering temperature or enhancing relative humidity. Moreover, dicamba volatilization was significantly reduced when treated maize experienced rainfall exceeding 1 mm. Notably, dicamba volatilization was more prominent from corn and soybean leaves compared to velvetleaf leaves and blotter paper. Despite growth chamber findings suggesting formulation-dependent volatility—where the acid form was the most volatile and inorganic salts were the least—field conditions revealed that employing less volatile formulations did not completely eliminate dicamba-induced symptoms on soybeans [55]. The relationship between weedicide vapor or particle flow and characteristic weather circumstances has not been thoroughly explored but is attain in recognition due to the growing employment of Plant Growth Regulator (PGR) herbicides in herbicide-resistant crops. Some instances of dicamba off-target movement have been proposed to be linked to temperature inversions. An inversion occurs when a layer of cool air rests close to the ground, with a layer of warmer air above it. Typically happening at dusk, dawn, and in windless circumstances, these inversions can trap tiny particles that may be carried by wind currents or downward air movements [8]. Analysis of data from the National Climate Reference Network (NCRN) covering the years 2012 to 2017 indicates that inversions tend to form on most evenings between May 15 and June 30, with minimal variation across soybean growing regions in the United States. The study confirmed that inversions can occur both before sunset and after sunrise, even in winds exceeding 4.8 km/h, scenarios where an inversion might not be anticipated [56]. Furthermore, non-site injury can happen at a substantial distance from the point of application, pivoting on the receptiveness of plants to a certainweedicide. With the increasing prevalence of weedicide resistance attributesin cultivable plants, the likelihood of non-site fluctuations also goes up [52].

Within just a couple of years in the market, dicamba has already exhibited several drift issues, resulting in harm to neighboring horticultural crops and native flora. In 2016, numerous instances of dicamba off-target movement were recorded due to unauthorized applications, as authorizations for in-plant use had not been approved [53]. In 2017, over 2700 cases were described where dicamba drifted non-site, affecting susceptible crops and estimated to impact more than 1.4 million hectares of soybeans [57]. These area assessments did not include the harm caused to other crops and adjacent broadleaf plants near agricultural fields. Despite alterations to the tag-marks and supplication demands for the 2018 cultivation season, there were still more than 1400 reported instances of non-site fluctuations. An ongoing argument regarding either the figure was under or over reported [58]. These incidents have presented significant disputes for the adoption of this latest innovation. In 2018, standardized label language (brand) was introduced for every one of the dicamba commodities, also mandatory tutoring for dicamba devices used for the purpose of application was implemented to mitigate non-site fluctuations. The non-site fluctuations of dicamba has accumulated widespread heed from the publishing communities and the general public. This attention poses a likely risk of extending to entire pesticides and weedicide-resistant plants, particularly given the under way discourse concerning the potential health effects on humans of glyphosate [27, 59]. The effects of emerging weedicide-resistantplant attributes and the corresponding changes in weedicide application practices on biodiversity remain unclear. Predictions suggest that these developments could have adverse consequences for local biodiversity within and around crop lands [60].

5. Conclusions

Given the swift emergence of glyphosate-resistant weed inhabitants, it is crucial to promptly identify and implement alternative weed management strategies [5]. While recent research has shown the effectiveness of various integrated weed management strategies against glyphosate-resistant weeds [61, 62]. The application of dicamba and 2,4-D may still serve as an constructive and successful weed control strategy in agricultural systems facing glyphosate-resistant plants [33]. The above mentioned emerging strategies might address the ineptitude in management of weeds and introduce diversity into weed control strategies within a brief timeframe. Nevertheless, the swift rise of glyphosate-resistant weeds underscores that weedicide-resistant plant biotechnology is rational only when integrated into broader, ecologically based weed control operations [7]. Implementing a range of weed management practices enables cultivators to safeguard the effectiveness of weedicide-resistant attributes and latest innovations in plants, reducing the likelihood of weeds developing resistance [5]. Although data substantiate the effectiveness of herbicide mixtures, such as those employed in newly stacked herbicide-resistant trait packages for herbicide resistance crops, in decelerating the progress of weedicide resistance in comparison to herbicide alternation [39], this approach is still viewed as merely postponing the inescapable when weedicides serve as the solitary weed management approach. Hence, the success of integrating several weedicide resistance attributes into plants hinges on the individual efficacy of each weedicide against the target weed species. This approach may not impede resistance if the target weed is by nowimmune more than one of the stacked attributes [16]. Furthermore, the interaction of judicious forces imposed by various weedicide vigorous components in piled up attributes might lead to the selection of both multiple herbicide resistance and non-target site resistance [45]. Implementing multiple sites of actions alongside integrated weed management within an agro ecological framework is crucial for enhancing the sustainability of weed management systems. Integrated Weed Management (IWM) advocates for a comprehensive approach to weed control, encompassing strategies like prevention, seedbank management, the integration of robotics and remote sensing technologies, intercropping, tillage, diverse crop rotations, biological controls, cover crops, and the utilization of varied and effectual weedicide sites of actions. Growers need to proactively embrace integrated weed management to responsibly incorporate new technologies. Hence, collaboration among growers, academics, and industry scientists is essential to prevail the obstacles hindering the acquisition of integrated weed management. Till the weed sciences fundamentally shifts its approach to weeds and their control by integrating biology and ecology, the constant challenges stemming from each new technological solution will fuel an ongoing progressive arms compete between emerging weedicide innovations and weedicide-resistant plants [63].

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