



Herbicides in modern sustainable agriculture: environmental fate, ecological implications, and human health concerns

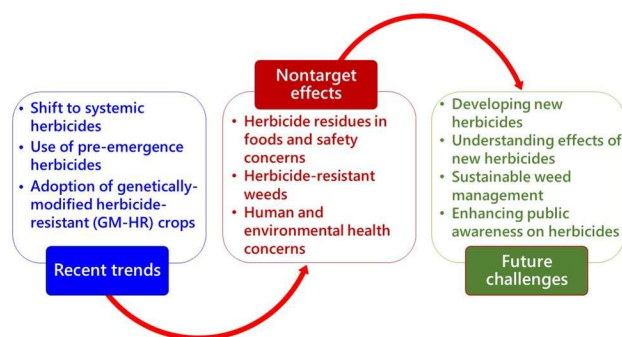
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Abstract

Herbicides play a crucial role in modern agriculture by controlling weeds and ensuring sustainable crop productivity. However, the use of herbicides has raised concerns regarding their contamination, posing serious threat to the environment, biodiversity, and food safety. Recent trends indicate a decline in the overall volume of herbicides usage, suggesting a shift towards more specific and targeted formulations of herbicides. Also, there has been an increased use of systemic and pre-emergence herbicides. The global agriculture still faces several challenges because of the adverse environmental impacts caused by herbicide contamination, both at the application site and offsite. In view of the growing concern, it is necessary to develop new herbicides with greater selectivity or bio-based herbicide that can degrade after successful control of the intended weed population and minimize or eliminate the environmental hazards. Furthermore, the adoption of integrated weed management practices rather than prolonged and repeated use of herbicide in agriculture can effectively reduce the growth of herbicide-resistant weed populations. The present review is a single valuable resource, providing insights into the recent trends and future challenges associated with herbicide use in modern agriculture, with a focus on human health and food safety. Also, we emphasize the advancements in herbicide technology, emergence of new herbicide-resistant weed species, regulatory considerations, and alternative approaches in herbicide use, all of which are particularly valuable to agroecology, policymakers, and stakeholders.

Graphical Abstract



Keywords Herbicides · Herbicide-resistant weeds · Nontarget effects · Food security · Human health hazards · Sustainable agriculture

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Introduction

The global population is expected to reach 9.20 billion by 2050, necessitating a 70% increase in agricultural productivity to ensure food security (Kagan 2016). According to the Food and Agriculture Organization (FAO 2001), approximately 50% of usable land worldwide is dedicated to agriculture. Within this cultivable land, farmers encounter various challenges, including weeds, insects, and fungal infestations, of which, weeds pose a significant obstacle to agricultural productivity (Curran 2016). Weeds in farmland compete with the crops for nutrients, space, light, and moisture, leading to a reduction in production ranging from 20 to 50%, depending on their intensity and duration in the field (Kaur et al. 2019). Different methods are employed to control weeds, such as manual or mechanical and chemical approaches (Rose et al. 2016). By far, chemical control has become the preferred and effective method of weed management in view of labor costs and the need for quick weed control and enhanced agricultural productivity with reduced cost (Sondhia 2014; Janaki et al. 2015). Consequently, herbicide application has become an integral part of modern agriculture, playing a crucial role in increasing production and keeping non-crop areas free from weeds (Cobb 2022). Currently, over 4.10 million tons of pesticides are consumed globally, with herbicides accounting for 47.50 followed by insecticides (29.50%), fungicides (17.50%), and others (5.50%) (Sharma et al. 2019a; Riedo et al. 2021). Since 1945, agricultural farmers in both developed and developing countries used more than 200 active ingredients of herbicides for weed management, accounting for over 25% of total pesticide consumption during the past decade (Green 2014). This growth in agrochemical production and consumption has been driven by robust economic expansion, including the agricultural and industrial sectors, particularly in the late nineteenth century (Sharma et al. 2019a).

Despite their role in increasing crop yields and ensuring food security, herbicides pose significant risks to human and environmental health due to the occurrence of these hazardous compounds in various environmental settings (Fernandes et al. 2020). When herbicides are applied in agricultural fields, urban areas, and forests, they can adversely affect both short- and long-term, humans, animals, insects, wildlife, and fish (Khan et al. 2023). Additionally, improper and excessive herbicide use can result in residues in plants and soils, crop toxicity, development of herbicide-resistant weeds, and harmful effects towards nontarget organisms (Sondhia 2014; Janaki et al. 2015). The consumption of agrochemicals poses significant

hazards due to the proximity between humans and the environment (Cioffi et al. 2021). Inappropriate handling of herbicides in farmlands can significantly impact crop, animal, and human health, while nontarget organisms can also be at risk due to herbicide residues entering the food chain (Singh and Singh 2016). The offsite migration of herbicides to surface water through runoff, leaching to groundwater, and volatilization into the air has detrimental effects towards nontarget organisms (Andreu and Picó 2004). Indeed, residues of persistent herbicides persist in crops, soil, water, and air for extended periods, posing potential hazards to human and environmental health (Sharma et al. 2019b). Given the intensive use of various herbicides in agriculture, it is crucial to determine the residues in different environmental settings to understand their overall fate and behaviour, which is greatly warranted for implementing effective risk management strategies (Mef-taul et al. 2020).

During the last decade, there has been a significant shift towards input-intensive agriculture. Various developments and strategies have emerged, including increased efforts by the agrichemical industry in discovering new herbicides, the adoption of genetically modified herbicide-resistant crops, breeding for weed-competitive crop cultivars and a greater reliance on systemic and new generation of pre-emergence herbicides (Beckie et al. 2019). These systemic and pre-emergence herbicides play crucial roles in modern agriculture and weed management strategies. Systemic herbicides are absorbed by plants and move through their vascular systems, effectively targeting weeds from the inside out, offering broad-spectrum control and efficiency (Amna et al. 2019). In contrast, pre-emergence herbicides, applied before weed growth, can prevent weed species from germinating, reduce competition with crops and ensure higher yields (Oliveira et al. 2020). Also, it minimizes the need for post-emergence herbicides, reducing overall chemical usage and environmental impact. Furthermore, recent trends indicate a decline in the overall volume of broad-spectrum herbicides used, accompanied by a shift towards more specific and targeted formulations (Damalas and Koutroubas 2018). These targeted formulations are designed to specific weeds or unwanted vegetation while minimizing harm to desired plants thereby reducing the overall amount of chemicals needed for effective weed control. One of the most notable changes in global herbicide-resistant weed management strategies has been the increased emphasis on reducing the weed seed bank and maintaining low seed bank levels through any possible means (Beckie et al. 2019). The evidence mounting on the adverse effects of agrochemicals on the environment and human health necessitates a transition



from the productivity-focused approach to sustainable and eco-friendly agriculture. Still, it is crucial that herbicides are formulated in a manner that allows them to degrade from the environment after fulfilling their intended purposes (Janaki et al. 2015; Sondhia 2014). The fate, ecological effects of herbicides and their residues have not been thoroughly understood in agricultural soils, and information available in the literature concerning the upcoming challenges in herbicide use for sustainable agriculture and food security is very limited and fragmentary. Therefore, this review is the first single source that aims to update and consolidate the existing literature in this research area by highlighting the emergence of new herbicide-resistant weed species, recent trends in herbicide use, developments in herbicide technology, regulatory considerations, and future challenges in developing alternative approaches of herbicide usage to ensure food security and safety, all of which are predominantly valuable for farmers, consumers, policymakers, and industry stakeholders.

Importance of herbicides in modern agriculture

Weeds are considered as a major obstacle in the modern farming system, as they reduce crop yield and quality, resulting in many billion dollars of crop losses annually (Abouziena and Haggag 2016). It is well documented that the losses caused by weeds have exceeded those from any category of agricultural pests, viz., insects, diseases, nematodes, rodents, etc. (Oerke 2006). Rao (2000) reported that the total annual losses of agricultural produce from weeds, insects, diseases, and other pests account for 45, 30, 20 and 5%, respectively. Globally, the estimated damage caused by weeds is around US \$40 billion per year (Abouziena and Haggag 2016), which is over \$26 billion in the USA alone, causing a major threat to food security (Délye et al. 2013). Consequently, herbicide use is the best way of controlling weed infestation in the agricultural farming system, offering easy application coupled with economic sustainability (Singh et al. 2020), quick action and efficient killing of approximately 90–99% of the targeted weeds (Délye et al. 2013). During the last century, herbicides became an unavoidable tool of agriculture, which allowed for a noticeable increase in crop yield to feed a rapidly growing human population (Carvalho 2017). Accordingly, global herbicide consumption has drastically increased by many folds, contributing to 47.50% of the total pesticide usage (Singh et al. 2020). Nearly, two thousand herbicide compounds have been discovered and put into application for the management of weeds in different arable

lands worldwide. It may either be applied to the soil during land preparation or directly to the foliage (Sherwani et al. 2015).

Pre-emergence herbicides are applied to the soil surface to kill weeds before the seedling emergence (Preisler et al. 2020). Examples of pre-emergence herbicides include imazethapyr, isoxaflutole, metolachlor, and pendimethalin (Mobli et al. 2020). Post-emergence herbicides are applied to weed seedlings that have already emerged and 2,4-D, imazethapyr, imazamox, and metribuzin are examples of post-emergence herbicides (Taran et al. 2013). The diversified groups of herbicides (Table 1) help to eradicate different weed species without disturbing crop plants (Vats 2015). Herbicides can also be classified based on their mechanism of action and chemical family. The mode of action refers to the specific biochemical or physiological process targeted by the herbicide (Fig. 1), while the chemical family represents the structural similarity among herbicides. A detailed classification based on the mode of action and chemical class is provided in Table 2. Also, herbicides are widely used as plant growth regulators in crops, gardens, and lawns (Sack et al. 2015). For instance, lower amounts of glyphosate can stimulate plant growth (the effect is termed hormesis), helps to ripen sugarcane and inhibits rust diseases in glyphosate-resistant wheat and soybean (Velini et al. 2010). In recent years, farmers rely more on herbicides in agricultural farming due to increased labour wages and sometime unavailability of agricultural labour. Thus, herbicides became a crucial component for controlling undesirable noxious weeds in modern agriculture.

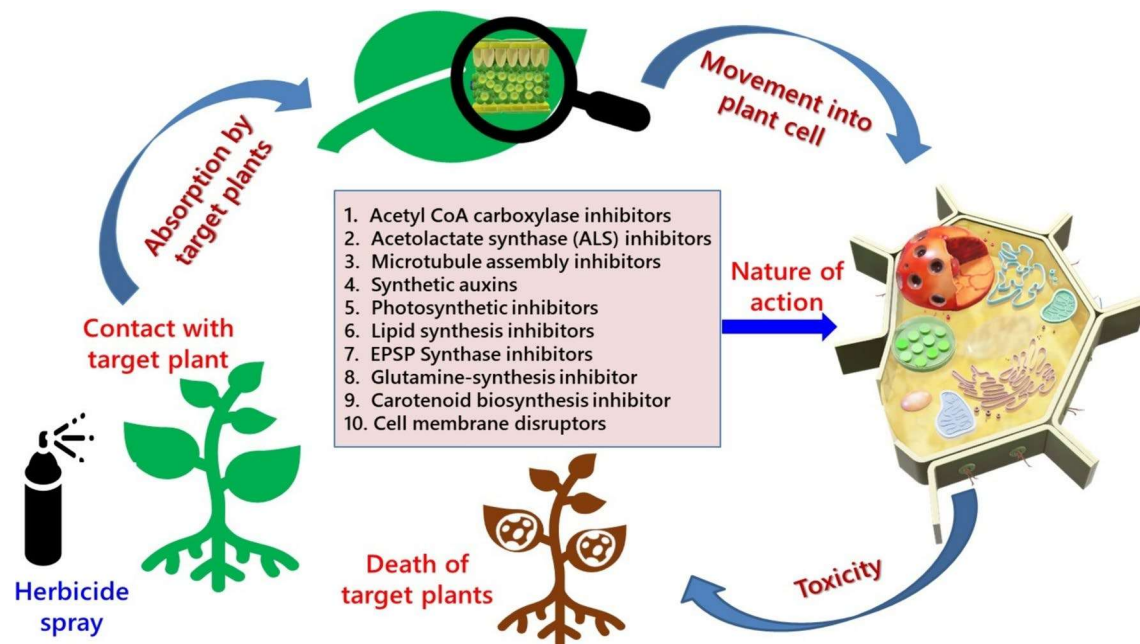
Recent trends in weed management

Recent trends in herbicide usage have been a subject of significant interest in the agricultural community over the past decade. However, the mode of action and human and environmental health effects of the formulations differ based on the chemical groups (Özkara et al. 2016). The recent trends in herbicide usage suggest a gradual decline in the overall volume of herbicides, accompanied by a shift towards more specific and targeted herbicide formulations (Damalas and Koutroubas 2018; Cech et al. 2022). This shift is largely attributed to increased awareness of the potential ecological and health risks associated with indiscriminate herbicide application (Devi et al. 2022). Additionally, advancements in precision agriculture technologies have played a crucial role in facilitating more efficient and targeted herbicide use (Kendall et al. 2022). These findings provide valuable insights for



Table 1 Most frequently used herbicides in agricultural settings

Chemical family	Herbicides	Agricultural crops	References
Organophosphorus	Glyphosate	Corn, soybean, wheat, cotton	Al-Rajab and Hakami (2014), Gunarathna et al. (2018), Maggi et al. (2020)
Phenoxy acid	2,4-D, MCPA	Rice, wheat, linseed	Crespin et al. (2001), Sondhia (2019)
Triazine	Atrazine, Simazine	Wheat, maize, canola, potato, beans	Singh et al. (2018), Sondhia (2019)
Bipyridiliums	Paraquat, Diquat	Canola, potato, pulses	Dennis et al. (2018), Kolberg et al. (2012), Marin-Morales et al. (2013)
Urea	Diuron	Cotton, sugar cane, alfalfa, wheat	Liu et al. (2010), Ngigi et al. (2011)
Chloroacetamide	Dimethenamid-P, Propanil, Acetochlor, S-Metolachlor, Alachlor, Metazachlor	Rice, soybean, canola, cotton, corn, peas	Westra (2012)
Dinitroaniline	Pendimethalin, Trifluralin	Rice, wheat, canola, peas, cabbage, carrot	Coleman et al. (2020), Sondhia (2019)
Benzoic acid	Dicamba	Corn, soybean, small grain crops	Egan and Mortensen (2012), Friesen (1965), Syguda et al. (2016)
Sulfonylurea	Metsulfuron methyl, Chlorsulfuron, Thifensulfuron	Wheat, rice corn	Kang et al. (2011), Sofo et al. (2012)
Pyrazole	Pyroxasulfone	Corn, field pea, sunflower, soybean	Khalil et al. (2018), Westra (2012)
Thiocarbamate	Prosulfocarb, EPTC	Wheat, barley, potatoes	Barba et al. (2020), Marín-Benito et al. (2018)

**Fig. 1** Modes of herbicide action in controlling weeds

farmers, policymakers, and industry stakeholders, aiding in the development of sustainable herbicide management strategies that balance weed control efficacy with environmental concerns (Li et al. 2020; Kendall et al. 2022).

Increased application of systemic herbicides

Nowadays, systemic herbicides have gained popularity due to their effectiveness in controlling weeds (Tsai 2019). For instance, glyphosate is a systemic herbicide that has been



Table 2 Classification of herbicides based on mode of action and chemical properties

Chemical classes	Herbicides	Mechanism of action	Effects on weeds	References
Aryloxyphenoxy propionate	Clodinafop, Cyhalofop-butyl, Diclofop, Fenoxaprop, Fluazifop-P, Quizalofop-P	Acetyl CoA carboxylase (ACC) inhibitors	Inhibit synthesis of fatty acids and destroy the membrane structure	Sherwani et al. (2015), Vats (2015)
Cyclohexanedione	Clethodim, Sethoxydim, Tralkoxydim			
Imidazolinone	Imazamethabenz, Imazamox, Imazapyr, Imazaquin, Imazapic, Imazethapyr	Acetolactate (ALS) synthase inhibitors	Inhibit production of three essential branched-chain amino acids (leucine, valine, and isoleucine)	Marin-Morales et al. (2013), Sherwani et al. (2015), Vats (2015)
Pyrimidinylthio-benzoate	Pyrithiobac			
Sulfonylamino-carbonyltriazolinone	Flucarbazonesodium, Propoxycarbazone			
Sulfonylurea	Chlorsulfuron, Chlorimuron, Bensulfuron, Halosulfuron, Mesosulfuron, Metsulfuron, Nicosulfuron, Primisulfuron, Prosulfuron, Sulfometuron, Thifensulfuron, Triasulfuron, Tribenuron, Florasulam			
Triazolopyrimidine	Flumetsulam, Cloransulamethyl, Diclosulam			
Dinitroaniline	Benefin, Ethalfuralin, Oryzalin, Pendimethalin, Prodimamine, Trifluralin	Microtubule assembly inhibitors	Inhibit cell division in plant roots	Sherwani et al. (2015), Vats (2015)
Pyridine	Dithiopyr, Thiazopyr			
None	DCPA			
Phenoxy	2,4-D, MCPA, 2,4-DB, 2,4-DP, Dichlorprop, MCPB, MCPP, Mecoprop,	Synthetic auxins	Interrupt cell growth in newly forming leaves and stem, cell wall plasticity and nucleic acid metabolism	Mensah et al. (2015), Vats (2015)
Benzoic acid	Dicamba			
Carboxylic acid	Picloram, Clopyralid, Triclopyr, Fluroxypyr			
Quinaline carboxylic acid	Quinclorac			



Table 2 (continued)

Chemical classes	Herbicides	Mechanism of action	Effects on weeds	References
Phenyl-carbamate	Desmedipham, Phenmedipham	Photosynthetic inhibitors at Photosystem II Site	Block electron transport at second stable electron acceptor of photosystem II which interrupt photosynthesis and energy production	Mensah et al. (2015), Sherwani et al. (2015), Vats (2015)
Pyridazinone	Pyrazon			
Triazine	Atrazine, Ametryn, Cyanazine, Prometon, Prometryn, Propazine, Simazine			
Triazinone	Hexazinone, Metribuzin			
Triazolinone	Amicarbazone			
Uracil	Bromacil, Terbacil			
Benzothiadiazole	Bentazon			
Nitrile	Bromoxynil, Ioxynil			
Phenyl-pyridazine	Pyridate			
Amide	Propanil			
Urea	Diuron, Fluometuron			
Thiocarbamates	Butylate, EPTC, Thiobencarb, Cycloate, Pebulate, Prosulfocarb, Molinate, Triallate, Vernolate	Lipid synthesis inhibitors	Reduce cuticular wax formation and inhibit shoot-growth	Mensah et al. (2015), Sherwani et al. (2015), Vats (2015)
Organophosphates	Glyphosate	EPSP (5-enolpyruvylshikimate-3-phosphate), Synthase Inhibitors	Inhibit the synthesis of aromatic amino acids	Mefaul et al. (2020), Mensah et al. (2015), Vats (2015)
None	Glufosinate	Glutamine-synthesis inhibitors	Accumulate huge ammonia and destroy plant cells	Sherwani et al. (2015), Vats (2015)
Triazoles	Amitrole	Carotenoid biosynthesis inhibitors/pigment synthesis inhibitors	Damage the chlorophyll pigments	Marin-Morales et al. (2013), Sherwani et al. (2015), Vats (2015)
Pyridazinone	Norflurazon			
Isoxazolidin-ones	Clomazone			
Diphenylethers	Acifluorfen, Fomesafen, Lactofen, Oxyfluorfen	Cell membrane disruptors or PPO inhibitors	Disrupt cell membrane	Marin-Morales et al. (2013), Mensah et al. (2015), Sherwani et al. (2015)
Bipyridylium	Diquat, Paraquat			
N-Phenylphthalimides	Flumiclorac			
Oxadiazoles	Oxadiazon			



widely used in agriculture for several decades due to its effectiveness against a wide range of weed species in various crop systems (Green 2009; Gage et al. 2019). However, concerns have been raised regarding the development of glyphosate-resistant weeds, prompting the need for alternative herbicides and management strategies (Duke and Powles 2009). Also, dicamba and 2,4-D has gained attention for its use as systemic herbicide to control broadleaf weeds in crops of soybean (*Glycine max* L.), cotton (*Gossypium hirsutum* L.), and genetically modified 2,4-D- and dicamba-tolerant soybeans in various agricultural and non-agricultural settings (Gage et al. 2019). However, dicamba has faced regulatory challenges and concerns about off-target movement, leading to restrictions on its use in some regions. Like dicamba, 2,4-D has been associated with concerns related to off-target movement and potential damage to sensitive crops and vegetation. Glufosinate is a non-selective systemic herbicide used primarily to control weeds in herbicide-tolerant crops of corn, soybeans, and cotton, and has gained popularity as an alternative to glyphosate in some cases (Sammons and Gaines 2014). However, the emergence of glufosinate-resistant weeds is a troubling issue that warrants careful attention and management strategies. As modern agriculture continues to evolve, it is necessary to address these challenges through innovative herbicide management strategies and explore sustainable alternatives to ensure the long-term efficacy of weed control in various crop systems.

Increased use of pre-emergence herbicides

In recent years, there has been a noticeable shift in usage towards pre-emergence herbicides. Pre-emergence herbicides are applied to the soil before the crop emerges, targeting weed seeds and seedlings in the soil, and these herbicides can effectively suppress weed growth before they emerge, and provide better weed control compared to post-emergence herbicides (Cioni and Maines 2010). This trend has gained traction due to several advantages offered by pre-emergence herbicides, such as increased effectiveness, reduced herbicide resistance, preventing weed from competing with crops for nutrients, water and light, and improved crop safety (Zimdahl 2018). Furthermore, herbicide resistance is a major concern in modern agriculture, where weeds develop genetic resistance to commonly used herbicides, by incorporating pre-emergence herbicides into weed management strategies, farmers can diversify their herbicide modes of action, reducing the risk of herbicide resistance development and preserving the efficacy of herbicides for longer periods (Cioni and Maines 2010; Gage et al. 2019).

Pre-emergence herbicides are typically applied before the crop has emerged and this timing allows for better selectivity, as the herbicide can be targeted to the soil where weed seeds are present, minimizing contact with emerging crop

plants, which reduces the risk of crop injury and enhances overall crop safety (Cioni and Maines 2010; Zimdahl 2018). Several pre-emergence herbicides have gained prominence in agricultural practices, and these include Group 14 herbicides (such as sulfentrazone and flumioxazin) and Group 15 herbicides (like acetochlor, metolachlor, and S-metolachlor), which effectively control both broadleaf weeds and grasses in crops of corn, soybeans, cotton, and peanuts (Umphres et al. 2018; Brabham et al. 2019; Rangani et al. 2021; Wang et al. 2021). In addition, Group 5 herbicides (such as metribuzin and flumioxazin) are employed for broad-spectrum weed control in crops like potatoes, soybeans, and peas (Ali et al. 2020; Hutchinson 2020) whereas Group 3 herbicides (like pendimethalin and trifluralin) exhibit selectivity in controlling grassy weeds and are widely used in various crops, including corn, wheat, and several vegetables (Chhokar et al. 2012; Parween et al. 2016). Therefore, the pre-emergence herbicides of Group 3, Group 5, Group 14, and Group 15 have become integral components of weed management in different crop types, ensuring efficient control of both broadleaf weeds and grasses.

Use of genetically modified herbicide-resistant crops

The phenomenon of adopting genetically modified (GM) herbicide-resistant crops has emerged as a prominent trend in herbicide usage within the agricultural sector over the past few decades (Meftaul et al. 2020). These crops are genetically engineered to tolerate specific herbicides, allowing farmers to control weeds more effectively while minimizing damage to the cultivated crops (Duke and Powles 2008; Owen et al. 2015). Notably, glyphosate-resistant crops such as soybeans, corn, cotton, and canola have gained widespread acceptance among farmers globally (Duke and Powles 2008). The introduction of glyphosate-resistant crops has led to increased reliance on glyphosate-based herbicides, like Monsanto's Roundup® (Belz and Duke 2014). The glyphosate-resistant crops have provided farmers with more flexibility and convenience in weed management, resulting in enhanced crop yields and reduced labor costs. Apart from glyphosate resistance, crops with resistance to other herbicides have also been developed and commercialized. For example, crops engineered to tolerate herbicides like glufosinate, 2,4-D, and dicamba have gained adoption in various regions (Shaner 2014). These herbicide-resistant crops provide farmers with additional options for weed control and help manage herbicide resistance by rotating the use of different herbicides (Gaines et al. 2010). The adoption of GM herbicide-resistant crops has provided several benefits to farmers, including improved weed control, increased crop yields, and reduced tillage (Powles and Yu 2010). However, there are concerns related to herbicide-resistant



weed evolution and the potential environmental impact of increased herbicide use (Heap 2019). The overreliance on a single herbicide or herbicide mode of action can lead to the selection of herbicide-resistant weed species, necessitating integrated weed management strategies (Powles and Yu 2010). The adoption of GM herbicide-resistant crops has undoubtedly transformed weed management practices in agriculture. However, it is essential to implement sustainable and integrated approaches to mitigate the challenges associated with herbicide resistance and environmental impacts, ensuring long-term food security, safety, and sustainability.

Herbicide resistance in weeds

Emergence of herbicide-resistant weed species

Globally, weed resistance to herbicides (Table 3) is ever-growing and is alarming for global food security (Délye et al. 2013). The continuous and long-term use of the same herbicide(s) with the same mechanism of action leads to changes in the weed population, and makes them resistant (Qasem 2011). For example, after the introduction of genetically modified (GR) herbicide resistance (HR) crops, the repeated and prolonged application of glyphosate over the past few decades has led to the emergence of resistance in certain weed species (Gage et al. 2019). Over time, resistant weeds reproduce successfully and become dominant in the population (Bo et al. 2017). The development of herbicide resistance is influenced by various factors, including herbicide chemistry, application rate, and non-chemical factors (Renton et al. 2014). The first reported case of herbicide resistance occurred in 1957, when wild carrot (*Daucus carota* L.) developed resistance to the herbicide 2,4-D in Canada, and since then, over two hundred weed species worldwide have been reported

to develop resistance to one or more herbicides (Délye et al. 2013). The highest number of herbicide-resistant weeds has been recorded in the USA (144), followed by Australia (62), Canada (59), France (35), and China (34) (Heap 2014). Herbicide resistance was not initially expected to be a significant problem before 1960; however, the discovery of common groundsel (*Senecio vulgaris* L.) weed population resistant to simazine or atrazine in 1968 raised concerns among the scientific community (Shaner 2014; Moss 2017). Examples of herbicide-resistant weeds include wild radish (*Raphanus raphanistrum* L.) in Australia, which developed resistance to 2,4-D and MCPA, prickly lettuce (*Lactuca serriola* L.) in the USA, resistant to 2,4-D, MCPA, and dicamba, and corn poppy (*Papaver rhoeas* L.) in Europe, resistant to phenoxy herbicides (Busi et al. 2018a). Glyphosate-resistant (GR) crops were commercially introduced in North and South America in 1996 (Shaner 2014). However, glyphosate resistance developed in different weed species due to repeated and continuous application of glyphosate (Fernández et al. 2017). The first glyphosate-resistant weeds were observed in *Lolium rigidum* in 1996 and *Eleusine indica* in 1997, after its frequent applications (5 to 10 times per year) for more than 15 years (Heap 2014). So, herbicide-resistant weeds continue to increase and pose a significant threat to crop production worldwide, affecting desirable plants and animals (Peterson et al. 2018).

Mechanisms of herbicide resistance

In modern agriculture, herbicide resistance poses a major challenge by diminishing the effectiveness of herbicides in controlling weed populations (Peterson et al. 2018). Studies revealed that several key mechanisms and causes contribute to herbicide resistance, and one such mechanism is target-site resistance (for example, resistance to ACCase

Table 3 First reports on global occurrence of herbicide resistance in weed species

Herbicide	Resistant weed	Scientific name	Nature of activity	Year of first report	References
2,4-D (Synthetic auxin)	Wild carrot	<i>Daucus carota</i> L	Affects cell wall plasticity and nucleic acid metabolism	1957	Délye et al. (2013)
Atrazine	Common groundsel	<i>Senecio vulgaris</i> L	PSII inhibitor	1968	Shaner (2014)
Glyphosate	Rigid ryegrass	<i>Lolium rigidum</i> L	EPSP synthase inhibitor	1996	Heap (2014)
Paraquat (Bipyridiliums)	Rigid ryegrass	<i>L. rigidum</i> L	Photosynthesis inhibitor	1970	Shaner (2014)
Trifluralin	Goosegrass	<i>Eleusine indica</i> L	Microtubule inhibitor	1973	Holt (1992)
Metasulfuron methyl	Wild radish	<i>Raphanus raphanistrum</i> L	ALS inhibitor	1982	Heap (1997)
Diclofop-methyl	Rigid ryegrass	<i>L. rigidum</i> L	ACCase inhibitors	1982	Heap (1997)
Chlortoluron (Ureas and amides)	Blackgrass	<i>Alopecurus myosuroides</i> Huds	Photosynthesis inhibitor	1985	Heap (1997)



inhibitor, ALS inhibitor, and PSII inhibitor), which occurs when genetic mutations in the target protein or enzyme responsible for herbicide binding or activity make it less susceptible to the herbicide's mode of action (Heap 2014; Moss 2017). These mutations can either arise spontaneously or through repeated exposure to herbicides. For instance, the target-site resistance mechanisms include altered target-site proteins, target-site gene amplification, and target-site overexpression (Heap 2014; Moss 2017). On the other hand, metabolic resistance is another type of resistance in which the weed enhances the metabolism or detoxification of herbicides, thereby reducing the concentration or activity of the herbicide within the plant (Yu and Powles 2014). This resistance is attributed to the overexpression or altered function of cytochrome P450 monooxygenases, glutathione transferases, or esterases, all involved in herbicide metabolism (Yu and Powles 2014). Weeds can also develop resistance by restricting herbicide uptake or translocation within the plant, thereby reducing the herbicide's effectiveness (Gressel 2015). The reduced uptake or translocation can result from changes in membrane permeability, the presence of active efflux transporters, or impaired translocation processes (Gressel 2015; Busi et al. 2018b). Furthermore, multiple resistance occurs when weeds exhibit resistance to more than one herbicide, often due to the accumulation of different resistance traits in a weed population or the horizontal transfer of resistance genes between species (Busi et al. 2017). Therefore, to successfully manage weed species that have developed resistance, it is crucial to understand the underlying mechanisms and causes of such resistance.

Environmental implications of herbicide use in modern agriculture

The environmental toxicity of herbicides is influenced by several factors, including the physicochemical properties of the herbicides, soil conditions, meteorological factors, application methods, frequency and quantity of use, and the biotic and abiotic characteristics of the environment (Tsai 2013; Fingler et al. 2017). Furthermore, the use of additives/adjuvants in combination with herbicide active ingredient can increase their toxicity to the surrounding environment and nontarget plants and animals (Gandhi et al. 2021). While adjuvants can enhance the performance of herbicides, they can also contribute to the formation of persistent residues in soil and plants, leading to potential adverse effects. For instance, the residue formation of trifluralin in soil and sugar beet roots was found to be higher ranging from 42 to 49% when adjuvants were used (Pacanoski 2015). The extensive use of herbicides also results in their accumulation in the environment, particularly in aquatic systems near agricultural areas, further contributing to toxicity concerns. Therefore, it is crucial to monitor the fate and behavior of herbicides in agricultural soil to assess their toxicity and minimize negative impacts on ecosystems (de Castro et al. 2017). Overall, Fig. 2 depicts the fate and movement of herbicides in diverse sections of the environment, while Table 4 presents the related data.

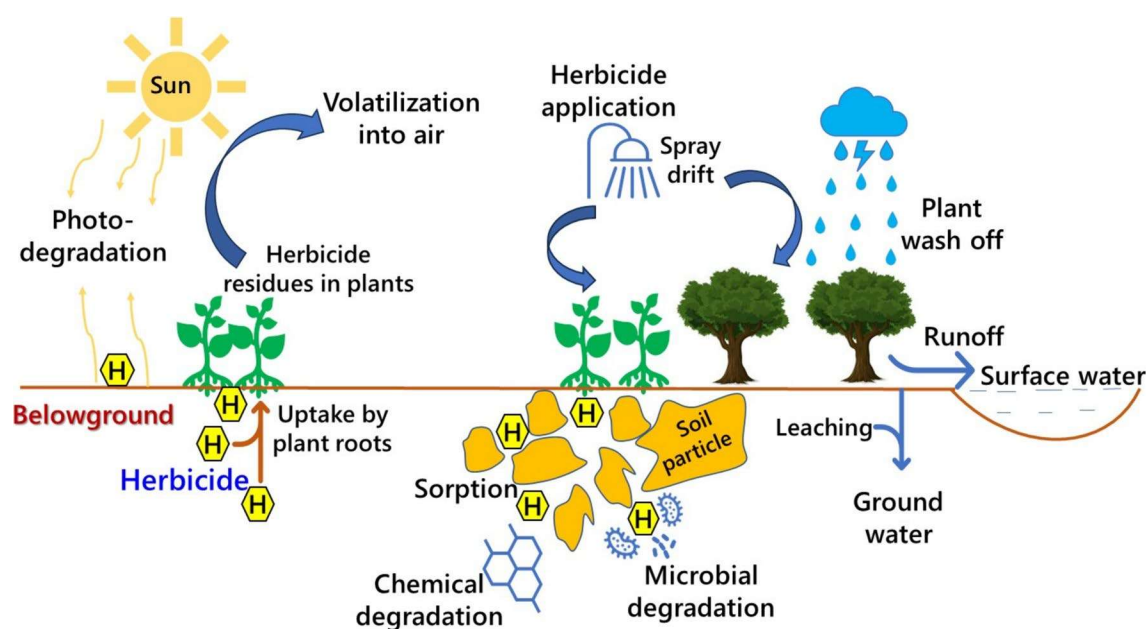


Fig. 2 Fate and movement of herbicides in different environmental settings



Table 4 Factors associated with the fate and movement of herbicides in the environment

Characteristic	Mechanism	Consequence	Factors involved	References
Persistence	Sorption–desorption	Accumulation and removal of herbicides due to interaction with soils, plants, and sediments	Organic matter, pH, clay particles, soil moisture, and textural composition	Blasioli et al. (2011), Schreiber et al. (2018)
Mobility	Surface runoff	Transport of herbicides due to excessive rainfall and irrigation	Climatic conditions, topography, soil texture, soil moisture content, herbicide formulation, and management practices	Kanissery et al. (2020), Tiryaki and Temur (2010)
	Leaching	Vertical movement downward through the soil	Irrigation or rainfall, water content, soil texture, clay, and organic matter contents	Blasioli et al. (2011), Tiryaki and Temur (2010)
	Volatilization	Loss of herbicides by evaporation from soil, water, and plants into the atmosphere	Vapor pressure, wind speed, temperature, soil texture, and size of spray drops	Blasioli et al. (2011), Tiryaki and Temur (2010)
	Drift	Movement of herbicides due to wind action	Size of spray drops, and wind speed	Blasioli et al. (2011)
Degradation	Microbial degradation	Breakdown or degradation of herbicides by microorganisms	Microbial diversity and activity, soil texture, moisture content, organic matter, pH, and temperature	Blasioli et al. (2011), Tiryaki and Temur (2010)
	Chemical degradation	Redox, hydrolysis, and ionization reaction	Soil pH, moisture, temperature, microbial activity, and organic matter content	Gavrillescu (2005), Kanissery et al. (2020), Tiryaki and Temur (2010)
	Photo-degradation	Breakdown of herbicides by sunlight	Duration of exposure and intensity of sunlight, properties of herbicides, depth, method of application, and climatic conditions	Gavrillescu (2005), Kanissery et al. (2020), Tiryaki and Temur (2010)

Mobility of herbicides in the environment

Herbicides can also spread from agricultural areas to other parts of the environment through spray drift, volatilization, runoff, and leaching, which can have detrimental effects on nontarget organisms as well as human and environmental health (Schreiber et al. 2018; Ramakrishnan et al. 2019). It has been shown that only 45% of the sprayed herbicides reach the target plants, while 30% is drifted, 10% is lost by runoff, leaching, and volatilization processes, and 15% reaches soil (Schreiber et al. 2018). The horizontal running of herbicides that are dissolved in water or adsorbed with eroding soil over a sloping surface is called surface runoff (Tiryaki and Temur 2010; Kanissery et al. 2020). In fact, the amount of runoff significantly depends on topography, soil texture, soil moisture content, herbicide formulation, climatic conditions, and management practices (Tiryaki and Temur 2010; Delcour et al. 2015). On the other hand, the mobility of herbicides in soil by water to a downward direction is known as leaching, which poses a potential threat to groundwater contamination (Kanissery et al. 2020). The characteristics of herbicides and soil, and their interaction with water from irrigation or rainfall, climatic conditions, and geography play a vital role in leaching (Tiryaki and Temur 2010). Also, leaching can be increased when the soil is sandy or the herbicide is water-soluble if rainfall occurs soon after spraying, and the herbicide is not strongly sorbed to the soil (Tiryaki and Temur 2010). Consequently, the weed-control efficiency, particularly pre-emergent herbicides, may decline (Kanissery et al. 2020). If runoff, which depends mostly on the addition of water (rainwater and irrigation water) to a field, is faster than the sorption of herbicides to soil, > 5% of the total applied chemical is lost that contaminates the environmental surface waters (Tiryaki and Temur 2010). Another most important transformation route of herbicides is volatilization, which occurs through evaporation from soil and plant material followed by dispersion into the aerial atmosphere by diffusion and turbulent mixing (Prueger et al. 2005) and later deposited in streams, rivers, and lakes (Thurman and Cromwell 2000; Kuang et al. 2003). Several factors affect herbicide volatilization from the soil, including the soil moisture content, herbicide's vapor pressure, sorption, water-solubility, soil texture, weather conditions, and size of spray drops (Tiryaki and Temur 2010; Blasioli et al. 2011). For instance, wet and sandy soils, hot, windy, or dry weather, and small spray drops increase volatilization of herbicides from soil to the atmosphere (Tiryaki and Temur 2010). Eventually, the volatilization of herbicide increases the risk of contaminating the atmosphere and consequently affecting nontarget organisms (Schreiber et al. 2018). In addition, other organic contaminants like PAHs and volatile contaminants can also move long distances and accumulate in soil, posing long-term health risks (Ambade



and Sethi 2021; Ambade et al. 2023). Climate change leads to rising temperatures and decreasing rainfall trends over time, causing adverse effects on agriculture (Meshram et al. 2018, 2020). Thus, developing sustainable weed management strategies along with adopting sustainable resource management practices is crucial to address environmental challenges (Javan et al. 2023; Sabah et al. 2023; Suseno and Basrowi 2023).

Persistence/degradation of herbicides in the environment

The persistence of herbicides or other agrochemicals in soil, plants, water, and the air is a raising global concern. Herbicides are considered persistent when they remain in soil long after their intended use, entering plants and potentially causing food toxicity (Helling 2005). The repeated application of the same herbicides contributes to their persistence due to slow degradation (Basu and Rao 2020). Herbicide persistence is measured by its half-life (DT_{50}), which represents the time it takes for 50% of the original quantity applied to break down in the soil (Helling 2005). Based on their relative persistence, herbicides can be categorized as long-lasting (> 6 months), moderate (3–6 months), low (1–3 months), or non-persistent (< 1 month) (Basu and Rao 2020). Long-lasting herbicides have a higher potential to spread in different parts of the environment through surface water and groundwater (Basu and Rao 2020). Herbicide residues tend to be less persistent on vegetation and plant canopies than in soil (Tiryaki and Temur 2010). But persistent herbicides can still pose a significant risk to human health when found in soil, surface, and groundwater, surrounding environments, and agricultural products (Qasem 2011). Therefore, it is crucial to avoid the use of persistent chemicals unless there are no alternative options and only when necessary. Triazines, sulfonylureas, uracils, bipyridiliums, phenylureas, dinitroanilines, imidazolinones, isoxazolidinones, and some plant growth regulators (Table 5) are known for their persistence (Janaki et al. 2015; Curran 2016).

In contrast, degradation is the major route of herbicide breakdown and reduce the concentration from soil and the

environment (Kanissery et al. 2020). Generally, degradation of herbicides occurs by biotic (via soil microorganisms) and abiotic (i.e., degradation by sunlight or chemical) processes (Lourencetti et al. 2012; Kanissery et al. 2020). Soil microorganisms (bacteria, fungi, and protozoans) facilitate biodegradation through metabolic or enzymatic process (Kanissery et al. 2020), which is the most crucial pathway responsible for the breakdown of herbicides (Curran 2016). These organisms utilize herbicides and organic matter or other substances as a source of energy and carbon (Tiryaki and Temur 2010), whereas some herbicides act as good sources of carbon and/or nitrogen for soil microorganisms (Kanissery and Sims 2011). The rate of biodegradation is proportional to microbial activity in soil, which is higher in areas with high organic matter, particularly in the soil surface horizons, and warm, humid, and well-aerated soil conditions (Tiryaki and Temur 2010). When microbial activity decreases in extremely alkaline or acidic soil, abiotic degradation or chemical degradation will be rapid (Tiryaki and Temur 2010), which occurs through oxidation–reduction, hydrolysis, and ionization reactions in soil (Kanissery et al. 2020). Photodegradation is another abiotic process of herbicide breakdown from soil surfaces, plant foliage, air, and water by the ultraviolet radiations of sunlight (Blasioli et al. 2011; Kanissery et al. 2020). Most of the herbicides are susceptible to photodegradation due to the presence of aromatic ring structures, heteroatoms, and other functional groups (Orellana-Garcia et al. 2014). Generally, the photolysis process is slower in water than in soil, and direct photolysis will occur within a shallow surface zone, approximately 0.20–0.30 mm vertical depth of soil (Konstantinou et al. 2001). Several factors affect the degradation of herbicides in soil, including soil properties like texture, organic matter content, pH, and microbial community, herbicide chemistry (solubility, log K_{ow}, vapor pressure, half-life, and log K_{oc}), climatic factors (temperature, rainfall, and aeration), and vegetation (Helling 2005). For example, no or minimal soil microbial activity results in persistence of glyphosate for up to 200 days in soils (Kanissery et al. 2020).

Table 5 Relative persistence of some herbicides in soil (based on Basu and Rao 2020; Janaki et al. 2015)

Relative persistence	Herbicides
< 1 months	Glyphosate, 2,4-D, MCPA
1–3 months	Alachlor, acetochlor, ametryn, anilofos, bispyribac-sodium, butachlor, carfentrazone-ethyl, dalapon, fluzifop-butyl, halosulfuron, metribuzin, metamifop, metsulfuron-methyl, metolachlor, oxyfluorfen, propachlor, pyrazosulfuron-ethyl, thiobencarb
3–6 months	Clomazone, chlorimuronethyl, diallate, dithiopyr, ethofumesate, fluchloralin, imazethapyr, isoproturon, metamitron, oxadiazon, linuron, pendimethalin, pyrazon
> 6 months	Atrazine, bromacil, chlorsulfuron, diuron, diquat, imazapyr, methazde, picloram, simazine, sulfometuron, sulfentrazone, trifluralin, paraquat



Food safety concern of herbicide residues

There are several issues associated with herbicide use, including overuse, improper application, incorrect selection, and harvesting crops immediately after herbicide application, which can result in higher levels of chemical residues in foods consumed by consumers (Handford et al. 2015; Meftaul et al. 2023). Depending on the level of exposure, these herbicide residues can have potential adverse effects on human health (Handford et al. 2015). Since food is a significant pathway for herbicide residues to enter the human body, it is crucial to monitor residue levels in food to ensure food safety (Zhang et al. 2015; Su et al. 2018). Most countries regulate pesticides using MRLs, which define the highest allowable amount of pesticide residue in food and feed when pesticides are correctly applied following Good Agricultural Practice (Handford et al. 2015; Wanwimolruk et al. 2015). Several countries, including Australia, India, Greece, China, Korea, Japan, Spain, etc., monitor pesticide residue levels in fruits, crops, and vegetables (Hasan et al. 2017). Plants can easily absorb residues from the soil, water, and air, transferring them through the food chain. For instance, herbicide residues were found to exceed MRLs in 6.60% of cereal samples in India (Sondhia 2014). Samples of food crops in Korea showed residues of 2,4-D at a concentration of 0.102 mg kg⁻¹, whereas 0.023–0.26 mg kg⁻¹ levels of glyphosate were detected in spinach and lettuce, respectively, grown in backyard garden soil in Australia (Shin et al. 2011; Meftaul et al. 2023). In Nigeria, crops of cassava, yam, potato, and groundnut had higher average concentrations of herbicide residues compared to leafy vegetables, with atrazine, 2,4-D, and paraquat occurring at 0.04, 0.02, and 0.67 mg kg⁻¹, respectively (Gushit et al. 2013).

If herbicides are applied close to the harvest date, large amounts of residues may be found in crops. For example, when pre-harvest Roundup was applied, glyphosate residues were found in two wheat varieties Major (11.10 mg kg⁻¹) and Walton (6.10 mg kg⁻¹) that are above the MRLs set by Health Canada (Xu et al. 2019). Diuron can persist in the environment for a long time and transfer trace amounts of residues to humans through the food chain, potentially affecting human health (Su et al. 2018). Since many fruits and vegetables are consumed raw, the possibility for the presence of pesticide residues in them is higher than in other crops (Stachniuk et al. 2017). However, even small amounts of herbicide residues in daily diets can lead to long-term health problems, including acute, chronic, or sub chronic difficulties (Gómez-Ramos et al. 2020). Consumers are already rejecting the use of hazardous chemicals in crop production to avoid chemical residues in food and ensure clean and safe consumption (Carvalho 2017). Therefore, to safeguard

consumer health and ensure food safety, it is essential to follow good agricultural practices (GAP) and continuously monitor herbicide residues to ensure food safety and minimize environmental health hazards (Prodhan et al. 2018).

Human health effects of herbicides

Human exposure to herbicides and health risks

The impact on human health associated with herbicide exposure is influenced by factors like the type of herbicide, dosage, exposure routes, and duration of exposure (Marin-Morales et al. 2013). Exposure to herbicides can occur through direct contact and inhalation in agricultural areas or indirectly through consumption of contaminated food and water (Anderson and Meade 2014), leading to acute and chronic health effects (Table 6). Prolonged exposure to herbicides can result in different types of cancer, neurodegenerative disorders, developmental and reproductive changes, and respiratory effects (Marin-Morales et al. 2013). For instance, glyphosate-based herbicides have been associated with endocrine disruption, liver and kidney damage, DNA damage, reproductive problems, and various neurodegenerative disorders (Thongprakaisang et al. 2013; Séralini et al. 2014; Kwiatkowska et al. 2017). Residues of glyphosate and its metabolite, AMPA, which can be found in water and agricultural products, are consumed by humans, and excreted through urine (Maheswari and Ramesh 2019). Similarly, atrazine herbicide contamination in drinking water has been linked to an increased risk of breast cancer in women, lower sperm counts in rural men, and decreased birth weight in children (Sankhla et al. 2018).

Another highly toxic herbicide, paraquat, with a lethal dose of 30 mg kg⁻¹ poses serious risks to human health, causing vomiting, nausea, diarrhea and fluid, and electrolyte loss upon ingestion (Tsai 2013). Acute exposure to paraquat through ingestion, inhalation, or dermal contact can lead to damage of heart, kidneys, liver, adrenal glands, muscles, and spleen as well as central nervous system, potentially resulting in multiple organ failure and death within 24 h. Dermal exposure to paraquat can cause dermatitis and skin burns, while accumulation in the lungs and kidneys has been associated with gall bladder cancer, lung cancer, and stomach cancer (Tsai 2013; Delirrad et al. 2015). Exposure to 2,4-D, 2,4,5-T, and MCPA can result in abdominal pain, vomiting, diarrhea, hypertension, headache, and gastrointestinal haemorrhage (Bradberry et al. 2000; Islam et al. 2018). Dermal or inhalational exposure to 2,4-D can cause skin irritation, itching, and breathing difficulties (Islam et al. 2018). The presence of 2,4-D has been detected in the



Table 6 Chronic diseases in humans upon exposure to herbicides

Herbicide	Chronic diseases	Sings and symptoms	References
2,4-D	Respiratory cancers, gall bladder cancer, and pancreatic cancer	Chronic cough, chest pain, fever, weight loss and fatigue, sensation in the nasopharynx and chest, dyspnea, loss of appetite, abdominal pain and cramping, weight loss, itchy skin, jaundice, lump in the abdomen, dark-colored urine, blood clots	Baiu and Visser (2018), Holly et al. (2004), Islam et al. (2018), Spiro et al. (2007)
Glyphosate	Breast cancer	Breast lump, breast pain, nipple abnormalities, breast skin abnormalities, breast swelling, breast infection or inflammation, change in the size or shape of the breast	Koo et al. (2017); Meftaul et al. (2020)
Pendimethalin	Rectal cancer, pancreatic cancer, and lung cancer	Abdominal pain, dark maroon or bright red blood in the stool, change in bowel habits, such as constipation, diarrhea, narrow stool, unexplained weight loss, dark-colored urine, blood clots, chronic cough, chest pain, fever, weight loss and fatigue, sensation in the nasopharynx and chest, dyspnea	Arici et al. (2020), Holly et al. (2004), John et al. (2011), Mostafalou and Abdollahi (2013), Spiro et al. (2007)
EPTC	Leukemia, colon cancer	Fever, fatigue, weakness, swollen lymph nodes, bleeding, musculoskeletal pain or dysfunction, frequent or severe infections, abdominal pain, change in bowel habits, such as diarrhea, constipation, dark maroon or bright red blood in the stool, narrow stool unexplained weight loss, weakness or fatigue	Davis et al. (2014), John et al. (2011), Mostafalou and Abdollahi (2013)
Trifluralin	Colon cancer	Abdominal pain, bright red blood in the stool, change in bowel habits, such as constipation, diarrhea, narrow stool, unexplained weight loss, weakness or fatigue	John et al. (2011), Mostafalou and Abdollahi (2013)
Simazine	Prostate cancer	Frequent urination, difficulty in passing urine, blood in the urine, disrupted urine flow, fever, headache, abdominal mass, lower abdominal pain, change in bowel habits, fatigue, pain in the back, hips, thighs, shoulders, or other bones, unexplained weight loss	Eke and Sapira (2002), Mostafalou and Abdollahi (2013)
Dicamba	Colon cancer, and lung cancer	Abdominal pain, change in bowel habits, such as diarrhea, constipation, bright red blood in the stool, narrow stool, unexplained weight loss, weakness or fatigue; chronic cough, chest pain, fever, sensation in the nasopharynx and chest, dyspnea	John et al. (2011), Mostafalou and Abdollahi (2013), Spiro et al. (2007)
Metolachlor	Lung cancer	Chronic cough, chest pain, fever, weight loss and fatigue, sensation in the nasopharynx and chest, dyspnea, nausea, vomiting, hemoptysis	Mostafalou and Abdollahi (2013), Spiro et al. (2007)
Paraquat	Gall bladder cancer, lung cancer, and stomach cancer	Loss of appetite, abdominal pain and cramping, weight loss, itchy skin, jaundice, lump in the abdomen; chronic cough, chest pain, fever, fatigue, sensation in the nasopharynx and chest, dyspnea, indigestion or feeling full after small meals, heartburn or indigestion, vomiting, with or without blood	Baiu and Visser (2018), Spiro et al. (2007), Torpy et al. (2010), Tsai (2013)
Imidazolinone	Bladder cancer	Loss of appetite, abdominal pain and cramping, weight loss, itchy skin, jaundice, lump in the abdomen	Alavanja and Bonner (2012), Baiu and Visser (2018)



urine samples of pregnant women ($120 \mu\text{g L}^{-1}$) and children ($2.90 \mu\text{g L}^{-1}$) living near farms in Ontario, Canada, indicating their potential exposure, and has been linked to respiratory cancers, gall bladder cancer, and pancreatic cancer among farmers and factory workers (Islam et al. 2018). The herbicide pendimethalin caused toxicity in applicators and their spouses, and its ingestion can lead to gastrointestinal damage, including nausea and epigastric pain (Arici et al. 2020). Long-term exposure to pendimethalin has been associated with an increased risk of rectal cancer, pancreatic cancer, and lung cancer among applicators (Mostafalou and Abdollahi 2013; Arici et al. 2020). Non-selective and non-biodegradable herbicides are particularly toxic and can persist in the environment for extended periods, posing a significant risk to humans and animals (Marin-Morales et al. 2013; Gupta 2018). Indiscriminate use or improper disposal of herbicide containers contributes to excessive herbicide exposure, resulting in more than one million deaths and numerous chronic diseases worldwide (Zhang et al. 2015; Gupta 2018).

Potential toxic effects toward other non-target organisms

The environmental impact of herbicides extends to nontarget organisms, including soil microorganisms, aquatic species, insects, birds, and other animals (Zhao et al. 2013). For example, glyphosate, has been found to negatively impact a wide range of organisms, from arthropods, fishes, reptiles, molluscs, amphibians, and birds (Gill et al. 2018). Glyphosate concentrations above 10 mg L^{-1} have been observed to hinder the growth of beneficial mycorrhizal fungi (*Thelephora americana*, *T. terrestris*, *Suillus tomentosus*, and *Hebeloma crustuliniforme*) and adversely affect earthworms, with reduced multiplication rates, DNA damage, loss of biomass, and diminished casting activity (Freemark and Boutin 1995; Gill et al. 2018). Bees, vital for pollination in both agricultural and wild plant species, are also negatively impacted by glyphosate (Belsky and Joshi 2020). The commercial formulation of glyphosate containing surfactant, polyethoxylated tallowamine (POEA) can be more toxic to terrestrial and aquatic animals as compared to pure glyphosate (Gandhi et al. 2021).

The long-term application of atrazine and 2,4-D can have detrimental effects on soil microorganisms, nitrogen-fixing bacteria, and enzyme production in soil (Rose et al. 2016). 2,4-D has adverse impact on the reproduction and development of earthworms and reduce the nitrogenase, phosphatase and hydrogen photoproduction activities of *Rhizobium* species and purple non-sulphur bacteria (Correia and Moreira 2010; Meena et al. 2020). Fish species (*Rhamdia quelen*) exposed to 2,4-D exhibited altered behavior, including lethargy and erratic swimming (de Castro et al. 2017). Dicamba, 2,4-D, and paraquat exerted high toxicity towards beneficial insects (Bohnenblust et al.

2016). The larvae of ladybird beetle (*Coleomegilla maculata*) are particularly vulnerable to the commercial formulation of 2,4-D, while dicamba decreased body weight and increased mortality (Freydier and Lundgren 2016). Indirect effects of herbicides pose a higher risk to habitats neighboring agricultural fields as compared to direct effects (Prosser et al. 2016). By reducing food sources of birds such as insects and grains, herbicides contribute to a decline in bird species in agricultural areas (Boatman et al. 2004). Further research is necessary to understand the fate and effects of newly released herbicides that are frequently used in agroecosystems. Figure 3 depicts the overall potential detrimental effects associated with the herbicide exposure to humans and other nontarget organisms.

Challenges and future research directions

Developing new herbicides with improved safety profiles

With growing concerns about the impact of herbicide residues on human and the environmental health, there is an urgent need to develop safer herbicides. Researchers are now focusing on developing herbicides that specifically target weed species while minimizing harm to nontarget organisms, which requires a deeper understanding of the molecular mechanisms underlying the weed growth to design herbicides that selectively inhibit these processes (Qu et al. 2021; Vasseghian et al. 2022). For instance, enzyme inhibitors and receptor-based herbicides offer more precise weed control to reduce the ecological impact, and it is crucial to develop herbicides that break down rapidly or firmly bind to soil particles, preventing their movement into groundwater or surface water (Casida and Durkin 2017; Qu et al. 2021). This can be achieved with biodegradable herbicides or formulations that enhance soil adsorption. However, selective herbicides that effectively eliminate weeds without harming crops are highly desirable (Takano et al. 2020; Torra et al. 2021). Future research should also be directed to develop new herbicides with greater selectivity, allowing farmers to target specific weed species while minimizing damage to agricultural crops (Torra et al. 2021). This can be accomplished through the cultivation of herbicide-resistant crop varieties or the use of herbicides that exploit physiological differences between crops and weeds.

The discovery and development of herbicides with innovative modes of action are critical for overcoming resistance of weed species (Qu et al. 2021; He et al. 2022). Research efforts are currently focused on identifying new target sites within weeds and developing herbicides that disrupt their essential processes, which includes assessing natural products, bio-based herbicides (sustainable alternatives to synthetic herbicides), and plant extracts with herbicidal properties (Damalas and Koutroubas 2018). Furthermore, researchers are exploring the use of herbicide combinations or stacked herbicide traits in genetically



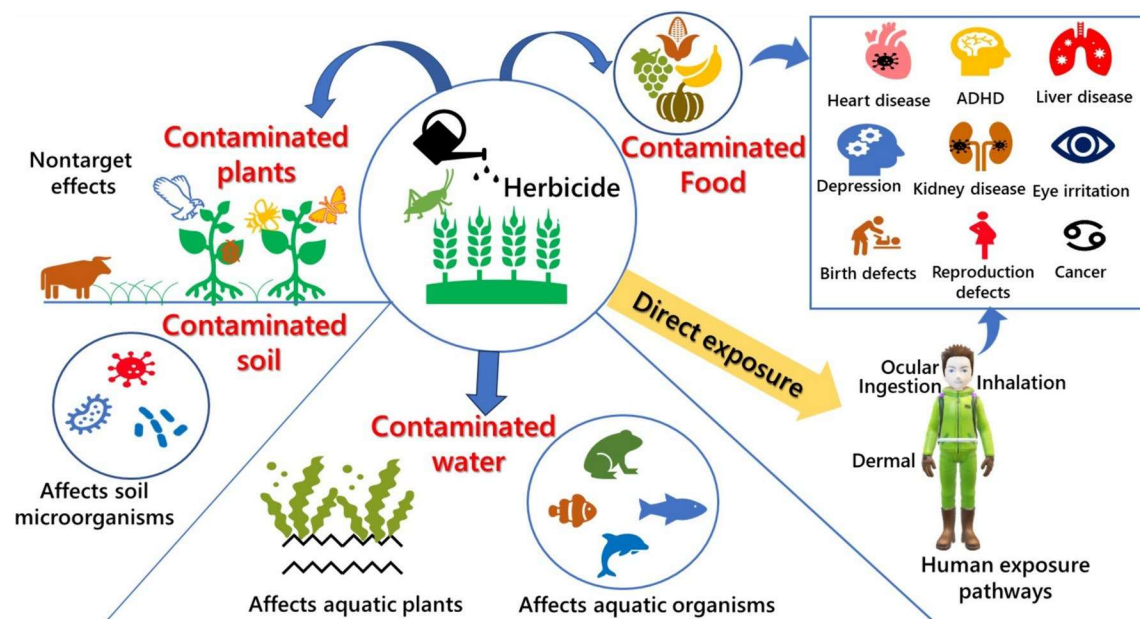


Fig. 3 Potential detrimental effects associated with herbicide exposure in humans and other nontarget organisms

modified crops (Vats 2015; Tsatsakis et al. 2017). By employing multiple herbicides with different modes of action, the risk of herbicide resistance can be minimized, and weed control effectiveness can be enhanced (Gage et al. 2019; Gaines et al. 2021). However, it is crucial to assess the potential synergistic or additive effects of these combinations on nontarget organisms and the environment. Future research should prioritize the improvement of methods for evaluating the environmental risks of herbicides, which involves assessing their impacts on soil health, water quality, beneficial organisms, and ecosystems. Developing standardized and robust testing protocols can facilitate the effective evaluation and regulation of new herbicides. Beyond the development of new herbicides, research should emphasize the promotion of sustainable weed management strategies which includes integrated weed management approaches that combine cultural, mechanical, biological, and chemical control methods. Implementing effective weed monitoring and decision support systems can optimize herbicide use and minimize environmental impacts.

Identifying sustainable weed management practices

The future of weed management poses several challenges that require research and innovative approaches. One crucial area to explore is the integration of multiple strategies, including cultural, biological, and chemical methods, to optimize effectiveness while minimizing the use of herbicides (Andrew et al. 2015; Bueno et al. 2021). Within an Integrated Weed Management (IWM) framework, it is essential to investigate the ideal combination and timing of

different weed management techniques to maximize control and minimize herbicide resistance (Riemens et al. 2022). Advanced technologies can play a significant role in sustainable weed management. The development of remote sensing, drones, and machine learning can enable real-time detection and mapping of weed populations, facilitating targeted herbicide application (Sishodia et al. 2020; Ghatrehsamani et al. 2023). Additionally, site-specific weed management techniques like variable-rate herbicide application, can optimize control while reducing environmental impact (Gerhards et al. 2022).

To explore more natural and eco-friendly options, research should focus on identifying and utilizing natural enemies like insects, pathogens, and allelopathic plants for weed suppression (Mehdizadeh and Mushtaq 2020; Hasan et al. 2021). Bacteria and fungi hold potential for bioherbicide development, offering effective and environmentally friendly weed control alternatives (Duke et al. 2018; Hasan et al. 2021). Furthermore, studying the impact of cover crops and diversified crop rotations on weed suppression, soil health, and crop productivity are crucial to reduce the reliance on herbicides and promote sustainable farming practices (Blanco-Canqui et al. 2015). Investigating the allelopathic potential of cover crops can provide a natural approach to inhibit weed germination and growth (Sturm et al. 2018). Preventing the replenishment of weed seed banks is another area of interest. For instance, strategies like seed predation by birds and insects, as well as seed burial through tillage practices, can be explored to minimize weed seed persistence (Saska and Honěk 2022). Techniques like seed dormancy-breaking and seedling



recruitment prediction models can be developed to target weed seeds and prevent their establishment (Storkey et al. 2021). In terms of herbicides, the focus should be on developing formulations with enhanced selectivity, lower environmental persistence, and reduced off-target effects (Heap and Duke 2018). Exploring new herbicide formulations (nanoformulations) and delivery systems (microencapsulation), can improve efficacy and minimize environmental impact (Li et al. 2021). It is essential to evaluate the economic and social implications of sustainable weed management practices to ensure their practical adoption by farmers (Bergtold et al. 2019). Moreover, assessing and developing policy frameworks that incentivize the adoption of sustainable weed management practices can promote long-term food safety and environmental sustainability (Mango et al. 2017; Buddenhagen et al. 2022).

Enhancing public awareness on herbicide safety

In the future, it is crucial to focus on improving public awareness and education regarding herbicide safety. This involves addressing misconceptions and promoting informed decision-making regarding the impact of herbicides on food safety (Katre et al. 2022). Engaging consumers in a constructive dialogue about herbicide safety should be a priority to achieve this, and educational campaigns and outreach programs should be developed, targeting consumers, farmers, and stakeholders (Douthwaite and Hoffercker 2017; Katre et al. 2022). To ensure accurate and accessible information on herbicide safety reaches the public, collaboration between regulatory bodies, agricultural organizations, and public health agencies is essential. These entities should work together to effectively communicate the risks and benefits associated with herbicide use and this can be achieved through clear communication of safety guidelines, regulations, and best practices (Benyam et al. 2021). It is important to empower individuals to make informed choices about their food consumption. To facilitate this, user-friendly online platforms and mobile applications should be developed to provide herbicide safety information (Nitin et al. 2020; Umapathi et al. 2022). Additionally, educational materials such as fact sheets and guidelines for safe herbicide handling and application should be made widely available (Ndayambaje et al. 2019). Incorporating herbicide safety information into agricultural extension services and training programs can further enhance awareness among farmers and those involved in the agricultural industry (Ngowi et al. 2016; Berni et al. 2021).

Collaboration between the agricultural industry, research institutions, and public health agencies should be fostered to promote joint initiatives for research, education, and outreach activities focused on herbicide safety (Ervin and Frisvold 2016; Berni et al. 2021). Engaging community

organizations and non-governmental organizations (NGOs) can also play a vital role in facilitating the dissemination of knowledge on herbicide safety (Wiedemann et al. 2022). Furthermore, conducting epidemiological studies to assess potential health effects of long-term herbicide exposure and longitudinal studies on the environmental persistence and impact of herbicide residues will contribute to a more comprehensive understanding of herbicide safety. Collaborative research efforts should be undertaken to evaluate the effectiveness of alternative weed management practices, reducing reliance on herbicides (Riemens et al. 2022). To ensure the integration of herbicide safety and sustainable agriculture education, it is important to incorporate these topics into school curricula. Encouraging student involvement in research projects and initiatives related to herbicide safety can foster innovation and a deeper understanding of the subject (Wiedemann et al. 2022). Eventually, supporting the development of educational resources and materials for young learners is crucial for building a solid foundation of knowledge on herbicide safety. By addressing these future challenges and focusing on research in these directions, can make significant progress in enhancing public awareness and education on herbicide safety.

Regulatory aspects associated with herbicide usage

Regulations associated with the herbicide usage encompass a complex web of policies and guidelines aimed at ensuring environmental safety, human health protection, and effective management of herbicidal products. Regulatory bodies worldwide often institute stringent measures governing the registration, sale, and application of herbicides, requiring thorough testing for toxicity, environmental impact, and efficacy before approval (Reeves et al. 2019; Valbuena et al. 2021). Additionally, herbicide labeling requirements detailing proper usage, safety precautions, and environmental risks are mandated to inform users adequately (Valbuena et al. 2021). Periodic reassessment and monitoring of herbicide residues in food, water, and soil are crucial for maintaining compliance with regulatory standards. Striking a balance between agricultural needs and environmental sustainability remains a continuous challenge in herbicide regulation.

Conclusions and future perspectives

The application of herbicides is crucial in modern agriculture worldwide. However, improper use of these chemicals can threaten human and environmental health. In fact, excessive and repeated use of herbicides over an extended period can lead to the development of resistance in weed



species toward specific weedicides. Furthermore, the off-site migration of herbicides through runoff and leaching can contaminate surface and groundwater, thereby adversely affecting aquatic organisms. Recent trends indicate a shift towards more precise and targeted formulations of herbicides, increased utilization of systemic and pre-emergence herbicides, and decreased overall herbicide usage. However, global agriculture encounters numerous challenges due to the adverse environmental impacts stemming from herbicide contamination, both at application site and offsite. Due to growing concerns, it is crucial to innovate herbicides with better selectivity or develop bio-based alternatives. Enzyme inhibitors and receptor-based herbicides can offer precise weed control and reduce ecological implications. Rapidly-degrading herbicides or those binding firmly to soil particles are needed to prevent groundwater or surface water contamination. Sustainable weed management practices, like using remote sensing, drones, and machine learning, can enable real-time weed detection and targeted herbicide application. Public awareness and constructive dialogue about herbicide safety should be prioritized through educational campaigns targeting consumers, farmers, and stakeholders.

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References

- Abouziena H, Haggag W (2016) Weed control in clean agriculture: a review. *Planta Daninha* 34:377–392
- Alavanja MC, Bonner MR (2012) Occupational pesticide exposures and cancer risk: a review. *J Toxicol Environ Health Part B* 15:238–263
- Ali L, Jo H, Song JT, Lee J-D (2020) The prospect of bentazone-tolerant soybean for conventional cultivation. *Agronomy* 10:1650
- Al-Rajab AJ, Hakami OM (2014) Behavior of the non-selective herbicide glyphosate in agricultural soil. *Am J Environ Sci* 10:94–101
- Ambade B, Sethi SS (2021) Health risk assessment and characterization of polycyclic aromatic hydrocarbon from the hydrosphere. *J Hazard Toxic Radioact Waste* 25:05020008
- Ambade B, Sethi SS, Chintalacheruvu MR (2023) Distribution, risk assessment, and source apportionment of polycyclic aromatic hydrocarbons (PAHs) using positive matrix factorization (PMF) in urban soils of East India. *Environ Geochem Health* 45:491–505
- Amna AHF, Hakeem KR, Qureshi MI (2019) Weed control through herbicide-loaded nanoparticles. *Nanomater Plant Potential*, pp 507–527.
- Anderson SE, Meade BJ (2014) Potential health effects associated with dermal exposure to occupational chemicals. *Environ Health Ins* 8:S15258
- Andreu V, Picó Y (2004) Determination of pesticides and their degradation products in soil: critical review and comparison of methods. *TrAC Trends Anal Chem* 23:772–789
- Andrew I, Storkey J, Sparkes D (2015) A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Res* 55:239–248
- Arici M, Abudayyak M, Boran T, Özhan G (2020) Does pendimethalin develop in pancreatic cancer induced inflammation? *Chemosphere* 252:126644
- Baiu I, Visser B (2018) Gallbladder cancer. *Jama* 320:1294–1294
- Barba V, Marín-Benito JM, Sánchez-Martín MJ, Rodríguez-Cruz MS (2020) Transport of ¹⁴C-prosulfocarb through soil columns under different amendment, herbicide incubation and irrigation regimes. *Sci Total Environ* 701:134542
- Basu S, Rao YV (2020) Environmental effects and management strategies of the herbicides. *Int J Biores Stress Manag* 11:518–535
- Beckie HJ, Ashworth MB, Flower KC (2019) Herbicide resistance management: recent developments and trends. *Plants* 8:161
- Belsky J, Joshi NK (2020) Effects of fungicide and herbicide chemical exposure on Apis and non-Apis bees in agricultural landscape. *Front Environ Sci* 8:81
- Belz RG, Duke SO (2014) Herbicides and plant hormesis. *Pest Manag Sci* 70:698–707
- Benyam AA, Soma T, Fraser E (2021) Digital agricultural technologies for food loss and waste prevention and reduction: global trends, adoption opportunities and barriers. *J Clean Prod* 323:129099
- Bergtold JS, Ramsey S, Maddy L, Williams JR (2019) A review of economic considerations for cover crops as a conservation practice. *Renew Agric Food Syst* 34:62–76
- Berni I, Menouni A, El IG, Duca R-C, Kestemont M-P, Godderis L, El Jaafari S (2021) Understanding farmers' safety behavior regarding pesticide use in Morocco. *Sustain Prod Consum* 25:471–483
- Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW, Francis CA, Hergert GW (2015) Cover crops and ecosystem services: Insights from studies in temperate soils. *Agron J* 107:2449–2474



- Blasioli S, Braschi I, Gessa CE (2011) The fate of herbicides in soil. Herbicides and environment. Intech, pp 175–195. <https://doi.org/10.5772/13056>
- Bo AB, Won OJ, Sin HT, Lee JJ, Park KW (2017) Mechanisms of herbicide resistance in weeds. *Kor J Agric Sci* 44:1–15
- Boatman ND, Brickle NW, Hart JD, Milsom TP, Morris AJ, Murray AW, Murray KA, Robertson PA (2004) Evidence for the indirect effects of pesticides on farmland birds. *Int J Avi Sci* 146:131–143
- Bohnenblust EW, Vaudo AD, Egan JF, Mortensen DA, Tooker JF (2016) Effects of the herbicide dicamba on nontarget plants and pollinator visitation. *Environ Toxicol Chem* 35:144–151
- Brabham C, Norsworthy JK, Houston MM, Varanasi VK, Barber T (2019) Confirmation of S-metolachlor resistance in Palmer amaranth (*Amaranthus palmeri*). *Weed Technol* 33:720–726
- Bradberry SM, Watt BE, Proudfoot AT, Vale JA (2000) Mechanisms of toxicity, clinical features, and management of acute chlorophenoxy herbicide poisoning: a review. *J Toxicol: Clin Toxicol* 38:111–122
- Buddenhagen CE, Bourdôt G, Cripps M, Bell N, Champion P, Dodd M, Eerens H, Ghanizadeh H, Griffiths A, Harrington K, Heenan P, Hulme PE, James T, Kean J, Lamoureaux S, Neal J, Ngow Z, Obadovic I, Orre-Gordona S, Percy H, Rolston P, Tozer K, Wynne-Jones B, Zydenbo S (2022) A horizon scan for temperate pastoral weed science—a New Zealand perspective. *NZ J Agric Res*, pp 1–17.
- Bueno AF, Panizzi A, Hunt TE, Dourado P, Pitta R, Gonçalves J (2021) Challenges for adoption of integrated pest management (IPM): the soybean example. *Neotrop Entomol* 50:5–20
- Busi R, Goggin DE, Heap IM, Horak MJ, Jugulam M, Masters RA, Napier RM, Riar DS, Satchivi NM, Torra J (2018a) Weed resistance to synthetic auxin herbicides. *Pest Manag Sci* 74:2265–2276
- Busi R, Porri A, Gaines TA, Powles SB (2018b) Pyroxasulfone resistance in *Lolium rigidum* is metabolism-based. *Pestic Biochem Physiol* 148:74–80
- Busi R, Porri A, Gaines T, Powles S (2017) Pyroxasulfone resistance in *Lolium rigidum* conferred by enhanced metabolic capacity. *bioRxiv* 116269.
- Carvalho FP (2017) Pesticides, environment, and food safety. *Food Energy Sec* 6:48–60
- Casida JE, Durkin KA (2017) Pesticide chemical research in toxicology: lessons from nature. *Chem Res Toxicol* 30:94–104
- Cech RM, Jovanovic S, Kegley S, Hertoge K, Leisch F, Zaller JG (2022) Reducing overall herbicide use may reduce risks to humans but increase toxic loads to honeybees, earthworms and birds. *Environ Sci Eur* 34:44
- Chhokar RS, Sharma RK, Sharma I (2012) Weed management strategies in wheat—a review. *J Wheat Res* 4:1–21
- Cioffi A, Mancini M, Gioia V, Cinti S (2021) Office paper-based electrochemical strips for organophosphorus pesticide monitoring in agricultural soil. *Environ Sci Technol* 55:8859–8865
- Cioni F, Maines G (2010) Weed control in sugarbeet. *Sugar Tech* 12:243–255
- Cobb AH (2022) Herbicides and plant physiology. Wiley, New York, pp. 1–363.
- Coleman NV, Rich DJ, Tang FH, Vervoort RW, Maggi F (2020) Biodegradation and abiotic degradation of trifluralin: a commonly used herbicide with a poorly understood environmental fate. *Environ Sci Technol* 54:10399–10410
- Correia F, Moreira J (2010) Effects of glyphosate and 2, 4-D on earthworms (*Eisenia foetida*) in laboratory tests. *Bull Environ Contam Toxicol* 85:264–268
- Crespin MA, Gallego M, Valcárcel M, González JL (2001) Study of the degradation of the herbicides 2,4-D and MCPA at different depths in contaminated agricultural soil. *Environ Sci Technol* 35:4265–4270
- Curran WS (2016) Persistence of herbicides in soil. *Crops Soils* 49:16–21
- Damalas CA, Koutroubas SD (2018) Current status and recent developments in biopesticide use. *Agriculture* 8:13
- Davis AS, Viera AJ, Mead MD (2014) Leukemia: an overview for primary care. *Am Fam Physic* 89:731–738
- de Castro MAC, de Souza CP, Fontanetti CS (2017) Herbicide 2,4-D: a review of toxicity on non-target organisms. *Water Air Soil Pollut* 228:120
- Delcours I, Spanoghe P, Uyttendaele M (2015) Literature review: impact of climate change on pesticide use. *Food Res Int* 68:7–15
- Delirrad M, Majidi M, Boushehri B (2015) Clinical features and prognosis of paraquat poisoning: a review of 41 cases. *Int J Clin Exp Med* 8:8122
- Délye C, Jasieniuk M, Le Corre V (2013) Deciphering the evolution of herbicide resistance in weeds. *Trends Gen* 29:649–658
- Dennis PG, Kukulies T, Forstner C, Orton TG, Pattison AB (2018) The effects of glyphosate, glufosinate, paraquat and paraquat-diquat on soil microbial activity and bacterial, archaeal and nematode diversity. *Sci Rep* 8:2119
- Devi PI, Manjula M, Bhavani R (2022) Agrochemicals, environment, and human health. *An Rev Environ Res* 47:399–421
- Douthwaite B, Hoffecker E (2017) Towards a complexity-aware theory of change for participatory research programs working within agricultural innovation systems. *Agric Syst* 155:88–102
- Duke SO, Powles SB (2008) Glyphosate: a once-in-a-century herbicide. *Pest Manag Sci* 64:319–325
- Duke SO, Powles SB (2009) Glyphosate-resistant crops and weeds: now and in the future. *AgBioForum* 12:346–357
- Duke SO, Owens DK, Dayan FE (2018) Natural product-based chemical herbicides. *Weed Control*; CRC Press, Boca Raton, pp 153–165
- Egan JF, Mortensen DA (2012) Quantifying vapor drift of dicamba herbicides applied to soybean. *Environ Toxicol Chem* 31:1023–1031
- Eke N, Sapira M (2002) Prostate cancer in Port Harcourt, Nigeria: features and outcome. *Nig J Sur Res* 4:34–44
- Ervin DE, Frisvold GB (2016) Community-based approaches to herbicide-resistant weed management: lessons from science and practice. *Weed Sci* 64:609–626
- FAO (2001) The State of Food and Agriculture Food & Agriculture Org., pp 48–255.
- Fernandes CLF, Volcão LM, Ramires PF, De Moura RR, Júnior FMRDS (2020) Distribution of pesticides in agricultural and urban soils of Brazil: a critical review. *Environ Sci Processes Impacts* 22:256–270
- Fernández P, Alcántara R, Osuna MD, Vila-Aiub MM, Prado RD (2017) Forward selection for multiple resistance across the non-selective glyphosate, glufosinate and oxyfluorfen herbicides in *Lolium* weed species. *Pest Manag Sci* 73(5):936–944
- Fingler S, Mendaš G, Dvorščak M, Stipičević S, Vasilčić Ž, Drevenkar V (2017) Herbicide micropollutants in surface, ground and drinking waters within and near the area of Zagreb, Croatia. *Environ Sci Pollut Res* 24:11017–11030
- Freydier L, Lundgren JG (2016) Unintended effects of the herbicides 2,4-D and dicamba on lady beetles. *Ecotoxicology* 25:1270–1277
- Friesen H (1965) The movement and persistence of dicamba in soil. *Weeds* 13:30–33
- Gage KL, Krausz RF, Walters SA (2019) Emerging challenges for weed management in herbicide-resistant crops. *Agriculture* 9:180
- Gaines TA, Zhang W, Wang D, Bukun B, Chisholm ST, Shaner DL, Nissen SJ, Patzoldt WL, Tranel PJ, Culpepper AS (2010) Gene amplification confers glyphosate resistance in *Amaranthus palmeri*. *Proc Nat Acad Sci* 107:1029–1034
- Gaines TA, Busi R, Küpper A (2021) Can new herbicide discovery allow weed management to outpace resistance evolution? *Pest Manag Sci* 77:3036–3041



- Gandhi K, Khan S, Patrikar M, Markad A, Kumar N, Choudhari A, Sagar P, Indurkar S (2021) Exposure risk and environmental impacts of glyphosate: highlights on the toxicity of herbicide co-formulants. *Environ Challen* 4:100149
- Gavrilescu M (2005) Fate of pesticides in the environment and its bioremediation. *Eng Life Sci* 5:497–526
- Gerhards R, Sanchez AD, Hamouz P, Peteinatos GG, Christensen S, Fernandez-Quintanilla C (2022) Advances in site-specific weed management in agriculture—a review. *Weed Res* 62:123–133
- Ghatrehsamani S, Jha G, Dutta W, Molaei F, Nazrul F, Fortin M, Bansal S, Debangshi U, Neupane J (2023) Artificial intelligence tools and techniques to combat herbicide resistant weeds—a review. *Sustainability* 15:1843
- Gill JPK, Sethi N, Mohan A, Datta S, Girdhar M (2018) Glyphosate toxicity for animals. *Environ Chem Lett* 16:401–426
- Gómez-Ramos MM, Nannou C, Bueno MJM, Goday A, Murcia-Morales M, Ferrer C, Fernández-Alba AR (2020) Pesticide residues evaluation of organic crops. a critical appraisal. *Food Chem X* 5:100079.
- Green JM (2009) Evolution of glyphosate-resistant crop technology. *Weed Sci* 57:108–117
- Green JM (2014) Current state of herbicides in herbicide-resistant crops. *Pest Manag Sci* 70:1351–1357
- Gressel J (2015) Dealing with transgene flow of crop protection traits from crops to their relatives. *Pest Manag Sci* 71:658–667
- Gunarathna S, Gunawardana B, Jayaweera M, Manatunge J, Zoysa K (2018) Glyphosate and AMPA of agricultural soil, surface water, groundwater and sediments in areas prevalent with chronic kidney disease of unknown etiology, Sri Lanka. *J Environ Sci Health Part B* 53:729–737
- Gupta PK (2018) Toxicity of herbicides. *Veterinary toxicology*. Elsevier, Amsterdam, pp. 553–567.
- Gushit JS, Ekanem EO, Adamu HM, Chindo IY (2013) Analysis of herbicide residues and organic priority pollutants in selected root and leafy vegetable crops in plateau state, Nigeria. *World J Anal Chem* 1:23–28
- Handford CE, Elliott CT, Campbell K (2015) A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. *Integ Environ Asses Manag* 11:525–536
- Hasan R, Prodhan M, Rahman S, Khanom R, Ullah A (2017) Determination of organophosphorus insecticide residues in country bean collected from different markets of Dhaka. *J Environ Anal Toxicol* 7:2161–525
- Hasan M, Ahmad-Hamdani MS, Rosli AM, Hamdan H (2021) Bioherbicides: an eco-friendly tool for sustainable weed management. *Plants* 10:1212
- He B, Hu Y, Wang W, Yan W, Ye Y (2022) The progress towards novel herbicide modes of action and targeted herbicide development. *Agronomy* 12:2792
- Heap IM (1997) The occurrence of herbicide-resistant weeds worldwide. *Pestic Sci* 51:235–243
- Heap I (2014) Global perspective of herbicide-resistant weeds. *Pest Manag Sci* 70:1306–1315
- Heap I, Duke SO (2018) Overview of glyphosate-resistant weeds worldwide. *Pest Manag Sci* 74:1040–1049
- Heap I (2019) The international survey of herbicide resistant weeds. *Weed Sci Org* Accessed: 27 March 2019.
- Helling CS (2005) The science of soil residual herbicides. *Soil residual herbicides: science and management*. *Top Can Weed Sci* 3:3–22
- Holly EA, Chaliha I, Bracci PM, Gautam M (2004) Signs and symptoms of pancreatic cancer: a population-based case-control study in the San Francisco Bay area. *Clin Gastroenterol Hepatol* 2:510–517
- Holt JS (1992) History of identification of herbicide-resistant weeds. *Weed Technol* 6:615–620
- Hutchinson PJ (2020) Weed management. In: *Potato production system*, pp 347–416
- Islam F, Wang J, Farooq MA, Khan MS, Xu L, Zhu J, Zhao M, Muñoz S, Li QX, Zhou W (2018) Potential impact of the herbicide 2,4-dichlorophenoxyacetic acid on human and ecosystems. *Environ Int* 111:332–351
- Janaki P, Sharma N, Chinnusamy C, Sakthivel N, Nithya C (2015) Herbicide residues and their management strategies. *Ind J Weed Sci* 47:329–344
- Javan K, Mirabi M, Hamidi SA, Darestani M, Altaee A, Zhou J (2023) Enhancing environmental sustainability in a critical region: climate change impacts on agriculture and tourism. *Civil Eng J* 9: No. 11.
- John S, George S, Primrose J, Fozard J (2011) Symptoms and signs in patients with colorectal cancer. *Colore Dis* 13:17–25
- Kagan CR (2016) At the nexus of food security and safety: opportunities for nanoscience and nanotechnology. *ACS Nano* 10:2985–2986
- Kang S, Chang N, Zhao Y, Pan C (2011) Development of a method for the simultaneous determination of six sulfonylurea herbicides in wheat, rice, and corn by liquid chromatography–tandem mass spectrometry. *J Agric Food Chem* 59:9776–9781
- Kanissery RG, Sims GK (2011) Biostimulation for the enhanced degradation of herbicides in soil. *Appl Environ Soil Sci*, p 843450.
- Kanissery R, Fenn R, Gairhe B, Kadyampakeni D (2020) Understanding the fate and persistence of herbicides in soils. *Citrus Ind News* 2020. <https://www.researchgate.net/publication/344751272>.
- Katre A, Bertossi T, Clarke-Sather A, Parsatoon M (2022) Agroecological transition: a territorial examination of the simultaneity of limited farmer livelihoods and food insecurity. *Sustainability* 14:3160
- Kaur P, Kaur P, Bhullar MS (2019) Environmental aspects of herbicide use under intensive agriculture scenario of Punjab. *Herbicide Residue Research in India*. Springer, Cham, pp 105–157.
- Kendall H, Clark B, Li W, Jin S, Jones GD, Chen J, Taylor J, Li Z, Frewer LJ (2022) Precision agriculture technology adoption: a qualitative study of small-scale commercial “family farms” located in the North China Plain. *Prec Agric* 23:319–351
- Khalil Y, Flower K, Siddique KH, Ward P (2018) Effect of crop residues on interception and activity of prosulfocarb, pyroxasulfone, and trifluralin. *PLoS ONE* 13:e0208274
- Khan BA, Nadeem MA, Nawaz H, Amin MM, Abbasi GH, Nadeem M, Ali M, Ameen M, Javaid MM, Maqbool R (2023) Emerging contaminants and plants: interactions, adaptations and remediation technologies. Springer, Cham, pp 109–134.
- Kolberg DI, Mack D, Anastassiades M, Hetmanski MT, Fussell RJ, Meijer T, Mol HGJ (2012) Development and independent laboratory validation of a simple method for the determination of paraquat and diquat in potato, cereals and pulses. *Anal Bioanal Chem* 404:2465–2474
- Konstantinou IK, Zarkadis AK, Albanis TA (2001) Photodegradation of selected herbicides in various natural waters and soils under environmental conditions. *J Environ Qual* 30:121–130
- Koo MM, von Wagner C, Abel GA, McPhail S, Rubin GP, Lyratzopoulos G (2017) Typical and atypical presenting symptoms of breast cancer and their associations with diagnostic intervals: Evidence from a national audit of cancer diagnosis. *Cancer Epidemiol* 48:140–146
- Kuang Z, McConnell LL, Torrents A, Meritt D, Tobash S (2003) Atmospheric deposition of pesticides to an agricultural watershed of the Chesapeake Bay. *J Environ Qual* 32:1611–1622
- Kwiatkowska M, Reszka E, Woźniak K, Jabłońska E, Michałowicz J, Bukowska B (2017) DNA damage and methylation induced by glyphosate in human peripheral blood mononuclear cells (in vitro study). *Food Chem Toxicol* 105:93–98



- Li W, Clark B, Taylor JA, Kendall H, Jones G, Li Z, Jin S, Zhao C, Yang G, Shuai C (2020) A hybrid modelling approach to understanding adoption of precision agriculture technologies in Chinese cropping systems. *Com Elect Agric* 172:105305
- Li N, Sun C, Jiang J, Wang A, Wang C, Shen Y, Huang B, An C, Cui B, Zhao X (2021) Advances in controlled-release pesticide formulations with improved efficacy and targetability. *J Agric Food Chem* 69:12579–12597
- Liu Y, Xu Z, Wu X, Gui W, Zhu G (2010) Adsorption and desorption behavior of herbicide diuron on various Chinese cultivated soils. *J Hazard Mater* 178:462–468
- Lourencetti C, De Marchi MR, Ribeiro ML (2012) Influence of sugar cane vinasse on the sorption and degradation of herbicides in soil under controlled conditions. *J Environ Sci Health Part B* 47:949–958
- Maggi F, la Cecilia D, Tang FH, McBratney A (2020) The global environmental hazard of glyphosate use. *Sci Total Environ* 717:137167
- Maheswari S, Ramesh A (2019) Fate and persistence of herbicide residues in India. In: *Herbicide Residue Research in India*. Springer, Cham pp. 1–27. https://doi.org/10.1007/978-981-13-1038-6_1
- Mango N, Siziba S, Makate C (2017) The impact of adoption of conservation agriculture on smallholder farmers' food security in semi-arid zones of southern Africa. *Agric Food Sec* 6:1–8
- Marín-Benito JM, Barba V, Ordax JM, Andrades MS, Sánchez-Martín MJ, Rodríguez-Cruz MS (2018) Application of green compost as amendment in an agricultural soil: effect on the behaviour of triasulfuron and prosulfocarb under field conditions. *J Environ Manag* 207:180–191
- Marin-Morales MA, Ventura-Camargo B, Hoshina MM (2013) Toxicity of herbicides: impact on aquatic and soil biota and human health. *InTech*, pp 399–443. <https://doi.org/10.5772/55851>
- Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK (2020) Impact of agrochemicals on soil microbiota and management: a review. *Land* 9:34
- Meftaul IM, Venkateswarlu K, Dharmarajan R, Annamalai P, Asaduzzaman M, Parven A, Megharaj M (2020) Controversies over human health and ecological impacts of glyphosate: is it to be banned in modern agriculture? *Environ Pollut Part A* 263:114372
- Meftaul IM, Venkateswarlu K, Parven A, Annamalai P, Megharaj M (2023) Human health risk assessment of pesticides in lettuce and spinach grown in urban backyard garden soils. *J Food Comp Anal* 115:104977
- Mehdizadeh M, Mushtaq W (2020) Biological control of weeds by allelopathic compounds from different plants: a bioherbicide approach. *Natural remedies for pest, disease and weed control*. Elsevier, Amsterdam, pp. 107–117.
- Mensah PK, Palmer CG, Odume ON (2015) Ecotoxicology of glyphosate and glyphosate-based herbicides—toxicity to wildlife and humans. *InTech* pp. 93–112. <https://doi.org/10.5772/60767>
- Meshram SG, Singh SK, Meshram C, Deo RC, Ambade B (2018) Statistical evaluation of rainfall time series in concurrence with agriculture and water resources of Ken River basin, Central India (1901–2010). *Theor Appl Climatol* 134:1231–1243
- Meshram SG, Kahya E, Meshram C, Ghorbani MA, Ambade B, Mirabasi R (2020) Long-term temperature trend analysis associated with agriculture crops. *Theor Appl Climatol* 140:1139–1159
- Mobli A, Rinwa A, Chauhan SBS (2020) Effects of sorghum residue in presence of pre-emergence herbicides on emergence and biomass of *Echinochloa colona* and *Chloris virgata*. *PLoS ONE* 15:e0229817
- Moss S (2017) Herbicide resistance in weeds. In: Horizons WRE, Hatcher PE, Froud-Williams RJ (eds) Wiley, Hoboken, New Jersey, pp 181–214
- Mostafalou S, Abdollahi M (2013) Pesticides and human chronic diseases: evidences, mechanisms, and perspectives. *Toxicol Appl Pharmacol* 268:157–177
- Ndayambaje B, Amuguni H, Coffin-Schmitt J, Sibon N, Ntawubizi M, VanWormer E (2019) Pesticide application practices and knowledge among small-scale local rice growers and communities in Rwanda: a cross-sectional study. *Int J Environ Res Public Health* 16:4770
- Ngigi A, Getenga Z, Boga H, Ndalut P (2011) Biodegradation of phenylurea herbicide diuron by microorganisms from long-term-treated sugarcane-cultivated soils in Kenya. *Toxicol Environ Chem* 93:1623–1635
- Ngowi A, Mrema E, Kishinhi S (2016) Pesticide health and safety challenges facing informal sector workers. *New Solutions: J Environ Occup Health Pol* 26:220–240
- Nitin K, Loc H, Chakravarthy AK (2020) Use of mobile apps and software systems for retrieving and disseminating information on pest and disease management. In: *Innovative pest management approaches for the 21st century*, pp 103–117. https://doi.org/10.1007/978-981-15-0794-6_6
- Oerke E (2006) Crop losses to pests. *J Agric Sci* 144:31
- Oliveira MC, Osipitan OA, Begcy K, Werle R (2020) Cover crops, hormones and herbicides: priming an integrated weed management strategy. *Plant Sci* 301:110550
- Orellana-Garcia F, Alvarez MA, Lopez-Ramon V, Rivera-Utrilla J, Sanchez-Polo M, Mota AJ (2014) Photodegradation of herbicides with different chemical natures in aqueous solution by ultraviolet radiation. Effects of operational variables and solution chemistry. *Chem Eng J* 255:307–315
- Owen MD, Beckie HJ, Leeson JY, Norsworthy JK, Steckel LE (2015) Integrated pest management and weed management in the United States and Canada. *Pest Manag Sci* 71:357–376
- Özkara A, Akyl D, Konuk M (2016) Pesticides, environmental pollution, and health. In: *Environmental health risk—hazardous factors to living species*, pp. 1–27. <https://doi.org/10.5772/63094>
- Pacanowski Z (2015) Herbicides and adjuvants. *InTech*, pp. 125–147. <https://doi.org/10.5772/60842>
- Parween T, Jan S, Mahmooduzzafar S, Fatma T, Siddiqui ZH (2016) Selective effect of pesticides on plant—a review. *Crit Rev Food Sci Nutri* 56:160–179
- Peterson MA, Collavo A, Ovejero R, Shivrain V, Walsh MJ (2018) The challenge of herbicide resistance around the world: a current summary. *Pest Manag Sci* 74:2246–2259
- Powles SB, Yu Q (2010) Evolution in action: plants resistant to herbicides. *Annu Rev Plant Biol* 61:317–347
- Preisler AC, Pereira AE, Campos EV, Dalazen G, Fraceto LF, Oliveira HC (2020) Atrazine nanoencapsulation improves pre-emergence herbicidal activity against *Bidens pilosa* without enhancing long-term residual effect on *Glycine max*. *Pest Manag Sci* 76:141–149
- Prodhan MDH, Papadakis EN, Papadopoulou-Mourkidou E (2018) Variability of pesticide residues in eggplant units collected from a field trial and marketplaces in Greece. *J Sci Food Agric* 98:2277–2284
- Prosser RS, Anderson JC, Hanson ML, Solomon KR, Sibley PK (2016) Indirect effects of herbicides on biota in terrestrial edge-of-field habitats: a critical review of the literature. *Agric Ecos Environ* 232:59–72
- Prueger JH, Gish TJ, McConnell LL, McKee LG, Hatfield JL, Kustas WP (2005) Solar radiation, relative humidity, and soil water effects on metolachlor volatilization. *Environ Sci Technol* 39:5219–5226
- Qasem JR (2011) Herbicides applications: problems and considerations. *InTech*, pp. 643–664. <https://doi.org/10.5772/12960>
- Qu RY, He B, Yang JF, Lin HY, Yang WC, Wu QY, Li QX, Yang GF (2021) Where are the new herbicides? *Pest Manag Sci* 77:2620–2625



- Ramakrishnan B, Venkateswarlu K, Sethunathan N, Megharaj M (2019) Local applications but global implications: can pesticides drive microorganisms to develop antimicrobial resistance? *Sci Total Environ* 654:177–189
- Rangani G, Noguera M, Salas-Perez R, Benedetti L, Roma-Burgos N (2021) Mechanism of resistance to S-metolachlor in *Palmer amaranth*. *Front Plant Sci* 12:652581
- Rao VS (2000) Principles of weed science. CRC Press, Boca Raton, ISBN 9781578080694. p. 566.
- Reeves WR, McGuire MK, Stokes M, Vicini JL (2019) Assessing the safety of pesticides in food: How current regulations protect human health. *Adv Nutr* 10(1):80–88
- Renton M, Busi R, Neve P, Thornby D, Vila-Aiub M (2014) Herbicide resistance modelling: past, present and future. *Pest Manag Sci* 70:1394–1404
- Riedo J, Wettstein FE, Rösch A, Herzog C, Banerjee S, Büchi L, Rl C, Wächter D, Martin-Laurent F, Bucheli TD (2021) Widespread occurrence of pesticides in organically managed agricultural soils—the ghost of a conventional agricultural past? *Environ Sci Technol* 55:2919–2928
- Riemens M, Sønderskov M, Moonen A-C, Storkey J, Kudsk P (2022) An integrated weed management framework: a pan-European perspective. *Eur J Agron* 133:126443
- Rose MT, Cavagnaro TR, Scanlan CA, Rose TJ, Vancov T, Kimber S, Kennedy IR, Kookana RS, Van Zwieten L (2016) Impact of herbicides on soil biology and function. *Adv Agron* 136:133–220
- Sabah N, Al-Mukhtar M, Shemal K (2023) Implementing management practices for enhancing water-food nexus under climate change. *Civil Eng J* 9:3108–3122
- Sack C, Vonderbrink J, Smoker M, Smith RE (2015) Determination of acid herbicides using modified QuEChERS with fast switching ESI+/ESI–LC-MS/MS. *J Agric Food Chem* 63:9657–9665
- Sammons RD, Gaines TA (2014) Glyphosate resistance: state of knowledge. *Pest Manag Sci* 70:1367–1377
- Sankhla MS, Kumari M, Sharma K, Kushwah RS, Kumar R (2018) Water contamination through pesticide & their toxic effect on human health. *Int J Res Appl Sci Eng Technol* 6:967–970
- Saska P, Honěk A (2022) Seed predation and weed seedbanks. In: Persistence strategies of weeds, pp. 144–164. <https://doi.org/10.1002/9781119525622.ch8>.
- Schreiber F, Scherner A, Andres A, Concenço G, Ceolin WC, Martins MB (2018) Experimental methods to evaluate herbicides behavior in soil. *Rev Brasil De Herbic* 17:71–85
- Séralini G-E, Clair E, Mesnage R, Gress S, Defarge N, Malatesta M, Hennequin D, de Vendômois JS (2014) Republished study: long-term toxicity of a Roundup herbicide and a Roundup-tolerant-genetically modified maize. *Environ Sci Eur* 26:1–17
- Shaner DL (2014) Lessons learned from the history of herbicide resistance. *Weed Sci* 62:427–431
- Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, Kohli SK, Yadav P, Bali AS, Parihar RD (2019a) Worldwide pesticide usage and its impacts on ecosystem. *SN Appl Sci* 1:1–16
- Sharma K, Tripathy V, Gopal M, Walia S (2019b) Good agricultural practices and monitoring of herbicide residues in India. In: herbicide residue research in India. Springer pp. 443–465. https://doi.org/10.1007/978-981-13-1038-6_16.
- Sherwani SI, Arif IA, Khan HA (2015) Modes of action of different classes of herbicides. InTech, pp. 165–186. <https://doi.org/10.5772/61779>.
- Shin EH, Choi JH, Abd El-Aty A, Khay S, Kim SJ, Im MH, Kwon CH, Shim JH (2011) Simultaneous determination of three acidic herbicide residues in food crops using HPLC and confirmation via LC-MS/MS. *Biomed Chromatogr* 25:124–135
- Singh B, Singh K (2016) Microbial degradation of herbicides. *Crit Rev Microbiol* 42:245–261
- Singh S, Kumar V, Chauhan A, Datta S, Wani AB, Singh N, Singh J (2018) Toxicity, degradation and analysis of the herbicide atrazine. *Environ Chem Let* 16:211–237
- Singh M, Singh N, Singh S (2020) Impact of herbicide use on soil microorganisms. In: Plant responses to soil pollution. Springer, Cham, pp. 179–194. https://doi.org/10.1007/978-981-15-4964-9_11.
- Sishodia RP, Ray RL, Singh SK (2020) Applications of remote sensing in precision agriculture: a review. *Remote Sens* 12:3136
- Sofo A, Scopa A, Dumontet S, Mazzatura A, Pasquale V (2012) Toxic effects of four sulphonylureas herbicides on soil microbial biomass. *J Environ Sci Health Part B* 47:653–659
- Sondhia S (2014) Herbicides residues in soil, water, plants and non-targeted organisms and human health implications: an Indian perspective. *Ind J Weed Sci* 46:66–85
- Sondhia S (2019) Environmental fate of herbicide uses in central India. In Herbicide residue research in India. pp. 29–104. Springer. https://doi.org/10.1007/978-981-13-1038-6_2
- Spiro SG, Gould MK, Colice GL (2007) Initial evaluation of the patient with lung cancer: symptoms, signs, laboratory tests, and paraneoplastic syndromes: ACCP evidenced-based clinical practice guidelines. *Chest* 132:149S–160S
- Stachniuk A, Szmagara A, Czeckzo R, Fornal E (2017) LC-MS/MS determination of pesticide residues in fruits and vegetables. *J Environ Sci Health Part B* 52:446–457
- Storkey J, Helps J, Hull R, Milne AE, Metcalfe H (2021) Defining integrated weed management: a novel conceptual framework for models. *Agronomy* 11:747
- Sturm D, Peteinatos G, Gerhards R (2018) Contribution of allelopathic effects to the overall weed suppression by different cover crops. *Weed Res* 58:331–337
- Su M, Jia L, Wu X, Sun H (2018) Residue investigation of some phenylureas and tebuthiuron herbicides in vegetables by ultra-performance liquid chromatography coupled with integrated selective accelerated solvent extraction-clean up in situ. *J Sci Food Agric* 98:4845–4853
- Suseno BD, Basrowi (2023) Role of the magnitude of digital adaptability in sustainability of food and beverage small enterprises competitiveness. *HighTech Innovat J* 4:270–282
- Syguda A, Borkowski A, Cyplik P, Marcinkowska K, Praczyk T, Pernak J (2016) Influence of oligomeric herbicidal ionic liquids with MCPA and Dicamba anions on the community structure of autochthonic bacteria present in agricultural soil. *Sci Total Environ* 563:247–255
- Takano HK, Ovejero RFL, Belchior GG, Maymone GPL, Dayan FE (2020) ACCase-inhibiting herbicides: mechanism of action, resistance evolution and stewardship. *Sci Agri* 78:e20190102
- Taran B, Holm F, Banniza S (2013) Response of chickpea cultivars to pre-and post-emergence herbicide applications. *Can J Plant Sci* 93:279–286
- Thongprakaisang S, Thiantanawat A, Rangkadilok N, Suriyo T, Satayavivad J (2013) Glyphosate induces human breast cancer cells growth via estrogen receptors. *Food Chem Toxicol* 59:129–136
- Thurman E, Cromwell AE (2000) Atmospheric transport, deposition, and fate of triazine herbicides and their metabolites in pristine areas at Isle Royale National Park. *Environ Sci Technol* 34:3079–3085
- Tiryaki O, Temur C (2010) The fate of pesticide in the environment. *J Biol Environ Sci* 4:29–38
- Torpy JM, Lynm C, Glass RM (2010) Stomach cancer. *Jama* 303:1771. <https://doi.org/10.1001/jama.303.17.1771>



- Torra J, Osuna MD, Merotto A, Vila-Aiub M (2021) Multiple herbicide-resistant weeds and non-target site resistance mechanisms: a global challenge for food production. *Front Plant Sci* 12:763212
- Tsai W-T (2013) A review on environmental exposure and health risks of herbicide paraquat. *Toxicol Environ Chem* 95:197–206
- Tsai W-T (2019) Trends in the use of glyphosate herbicide and its relevant regulations in Taiwan: a water contaminant of increasing concern. *Toxics* 7:4
- Tsatsakis AM, Nawaz MA, Kouretas D, Balias G, Savolainen K, Tutelyan VA, Golokhvast KS, Lee JD, Yang SH, Chung G (2017) Environmental impacts of genetically modified plants: a review. *Environ Res* 156:818–833
- Umapathi R, Rani GM, Kim E, Park SY, Cho Y, Huh YS (2022) Sowing kernels for food safety: importance of rapid on-site detection of pesticide residues in agricultural foods. *Food Front* 3:666–676
- Umphres AM, Steckel LE, Mueller TC (2018) Control of protoporphyrinogen oxidase inhibiting herbicide resistant and susceptible Palmer amaranth (*Amaranthus palmeri*) with soil-applied protoporphyrinogen oxidase-inhibiting herbicides. *Weed Technol* 32:95–100
- Valbuena D, Cely-Santos M, Obregón D (2021) Agrochemical pesticide production, trade, and hazard: Narrowing the information gap in Colombia. *J Environ Manage* 286:112141
- Vasseghian Y, Arunkumar P, Joo S-W, Gnanasekaran L, Kamyab H, Rajendran S, Balakrishnan D, Chelliapan S, Klemeš JJ (2022) Metal-organic framework-enabled pesticides are an emerging tool for sustainable cleaner production and environmental hazard reduction. *J Clean Prod* 133966
- Vats S (2015) Herbicides: history, classification and genetic manipulation of plants for herbicide resistance. *Sustain Agric Rev* 15:153–192
- Velini ED, Trindade ML, Barberis LRM, Duke SO (2010) Growth regulation and other secondary effects of herbicides. *Weed Sci* 58:351–354
- Wang D, Wang B, Xi Z (2021) Development of protoporphyrinogen IX oxidase inhibitors for sustainable agriculture. In: *Crop protection products for sustainable agriculture*. ACS Pub, USA, pp. 11–41. <https://doi.org/10.1021/bk-2021-1390.ch002>
- Wanwimolruk S, Kanchanamayoon O, Phopin K, Prachayasittikul V (2015) Food safety in Thailand 2: Pesticide residues found in Chinese kale (*Brassica oleracea*), a commonly consumed vegetable in Asian countries. *Sci Total Environ* 532:447–455
- Westra EP (2012) Adsorption, leaching, and dissipation of pyroxasulfone and two chloroacetamide herbicides. Colorado State University Libraries. <http://hdl.handle.net/10217/69216>
- Wiedemann R, Stamm C, Staudacher P (2022) Participatory knowledge integration to promote safe pesticide use in Uganda. *Environ Sci Pol* 128:154–164
- Xu J, Smith S, Smith G, Wang W, Li Y (2019) Glyphosate contamination in grains and foods: an overview. *Food Control* 106:106710
- Yu Q, Powles SB (2014) Resistance to AHAS inhibitor herbicides: current understanding. *Pest Manag Sci* 70:1340–1350
- Zhang M, Zeiss MR, Geng S (2015) Agricultural pesticide use and food safety: California's model. *J Integ Agric* 14:2340–2357
- Zhao J, Neher DA, Fu S, Za Li, Wang K (2013) Non-target effects of herbicides on soil nematode assemblages. *Pest Manag Sci* 69:679–684
- Zimdahl RL (2018) *Fundamentals of weed science*, 5th edn. Academic Press, New York. <https://doi.org/10.1016/C2015-0-04331-3>

