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Weeds and Weed Control Mechanism

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ABSTRACT

Weeds are opportunistic plant species that thrive in disturbed environments, often interfering with agricultural productivity and ecological balance. This review synthesizes definitions, classifications, ecological roles, and control mechanisms of weeds, highlighting their dual nature as both problematic and beneficial organisms. Weeds contribute to biodiversity, soil stabilization, and medicinal resources, yet they also compete with crops, harbor pests, and reduce yields. The persistence of weeds is largely driven by seed bank dynamics and adaptive traits such as prolific seed production, dormancy, and vegetative propagation. Control strategies are categorized into physical, cultural, biological, and chemical methods, each with distinct advantages and limitations. The paper emphasizes the need for integrated weed management approaches that combine traditional practices with modern innovations, including allelopathy, bioherbicides, and precision agriculture. By critically examining weed ecology and management, this review provides a framework for sustainable solutions to weed-related challenges in agricultural and ecological systems.

Highlights

- Weeds influence both agricultural productivity and ecosystem functions.
- Integrated weed management offers sustainable long-term weed suppression.
- Precision agriculture and bioherbicides are shaping future weed control.

Introduction

Weeds have long been recognized as one of the most persistent challenges in agriculture and ecology. They have been variously defined as plants growing out of place (WSSA, 1956), species not intentionally sown but exhibiting competitive and aggressive behavior (Brenchley, 1920), plants whose potential uses remain undiscovered (Emerson, 1878), or vegetation that colonizes habitats heavily modified by human activity (Harper, 1944). Other definitions emphasize their persistence, resistance to control (Gray, 1879), and unsightly growth in cultivated lands (Thomas, 1956). These diverse perspectives highlight the difficulty of arriving at a universal definition of weeds.

Crawley (1997) noted that weediness is context-dependent, suggesting that a plant becomes a weed only when its abundance exceeds a threshold level. This view underscores the role of human

perception in determining weed status, as the same species may be considered useful in one context and undesirable in another. Baker's influential work (1965, 1974) further refined the concept by identifying reproductive traits (early flowering, prolific seed production, vegetative propagation), physiological traits (rapid growth, allelopathy, seed dormancy), and ecological traits (plasticity and adaptability) as hallmarks of successful weeds. He thus, defining a weed, wrote that "A plant is a weed if, in any specified geographical area, its populations grow entirely or predominantly in situations markedly disturbed by man (without, of course, being deliberately cultivated plants). His framework has been widely applied in weed ecology and invasion biology to predict which species are likely to become problematic. However, as Booth *et al.* (2003) cautioned, not all plants with these traits are weeds, and not all weeds necessarily exhibit them.

The anthropocentric view of weeds, as plants interfering with human activities, provides limited insight into their ecological roles. Weeds are opportunistic species whose strategies enable them to thrive in disturbed environments. Their prolific seed production, rapid germination, and ability to exploit open niches allow them to outcompete crops and desirable vegetation. At the same time, weeds may provide ecological services such as biodiversity support, erosion control, and even medicinal resources. Thus, whether a plant is considered a weed depends on ecological context, human objectives, and socio-economic perceptions (Zimmerman, 1976; Aldrich, 1984; Rejmánek, 2000).

In agricultural systems, weeds represent a major constraint to productivity, often causing greater yield losses than any other pest group (Fried *et al.*, 2017; Bulu, 2023). Their persistence is a consequence of the interaction between human disturbance and plant ecological traits. Effective management therefore requires integrated approaches that combine ecological understanding with practical control strategies. This review synthesizes current knowledge on weed ecology and control mechanisms, providing a framework for addressing weed-related challenges in both agricultural and ecological contexts.

Classification of Weeds

There are many ways in which weeds can be classified into groups for convenience of planning, interpreting and taking control measures against them. Weeds can be classified based on morphology or growth habit, life cycle (ontogeny), botanical consideration, and habitat (Figure 1).

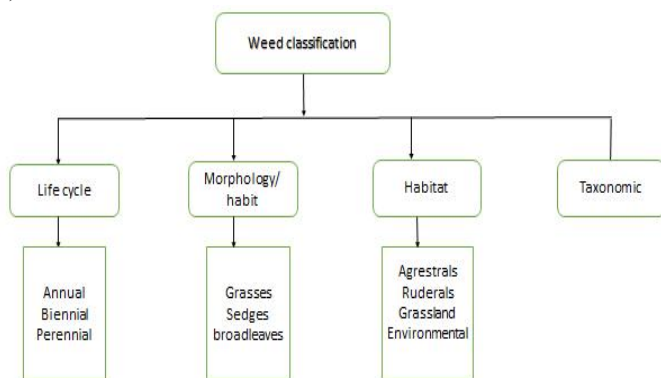


Fig 1: Classification of weeds

Taxonomic classification of weeds

Akobundu and Agyakwa (1998) classified the weed of West Africa into 53 families of which 21 are aquatic weeds or weeds of lowland area and the remaining, weeds of dry land. The dry land weeds were further classified into dicotyledonous and monocotyledonous weeds of arable land.

In the dicotyledonous, families such as Amaranthaceae (*Amaranthus spinosus* and *Alternanthera sessilis*), Malvaceae (*Urena lobata*), Asteraceae (*Aspilia africana* and *Ageratum conyzoides*), Euphorbiaceae (*Euphorbia hirta* and *Phyllanthus amarus*) leguminosae (*Daniella oliveria*, *Senna hirsuta* and *Mimosa pudica*) and the Rubiaceae (*Mitracarpus villosus* and *Oldenlandia corymbosa*) are largely represented while Commelinaceae (*Aneilema aequinoctiale* and

Commelina diffusa), Cyperaceae (*Cyperus esculentus* and *Mariscus flabelliformis*), Dennstaedtiaceae (*Pteridium aquilinum*) and the Poaceae (*Andropogon gayanus* and *Ixonopus compressus*) are the monocotyledonous families presented (Akobundu and Agyakwa, 1998).

Classification based on life cycle

Weeds are also classified based on the duration of their life cycle i.e., the length of life, season of growth, and time and method of reproduction (Radosevich *et al.*, 2007; Zimdahl and Basinger, 2024). Annual weeds are those that live only for a season or a year and complete their life cycles in that season or year (Radosevich *et al.*, 2007). These are small herbs with shallow roots and weak stem that produce seeds in profusion and the mode of propagation is commonly through seeds. After seeding, the annuals die away and their seeds germinate and start the next generation in the next season or year e.g. *Commelina benghalensis*, *Boerhavia erecta* and *Pennisetum* spp. Biennials live for more than one year but less than two. In the first season, they grow vegetatively into a leafy rosette, often resembling winter annuals (Radosevich *et al.*, 2007). After a cold period, they resume growth, produce flowers and seeds, and then die. They are usually large at maturity with thick, fleshy roots, and are found mainly in non-cropped areas (e.g., *Taraxacum officinale*). Few weeds are true biennials, though some annuals may behave like them under certain conditions, and some biennials may persist as short-lived perennials in mild climates (Radosevich *et al.*, 2007).

Perennials live for more than two years and may live almost indefinitely (Holzner 1982; Radosevich *et al.*, 2007). They are adapted to withstand adverse conditions and propagate not only through seeds but also by underground stems, root, rhizomes, tubers etc. (Radosevich *et al.*, 2007). Thus they are further classified into simple perennials; propagated by seeds alone e.g. *Sonchus arvensis*, bulbous perennials; weeds which possess a modified stem with scales and reproduce mainly from bulbs and seeds, Corm perennials; plants that possess a modified shoot and fleshy stem and reproduce through corm and seeds e.g. *Phleum pretense*. Creeping perennials; reproduced through seeds as well as with rhizome e.g. *Sorghum halapense* or reproduce through stolon e.g. *Cynodon dactylon*.

Classification based on habitat

Another way to categorize weeds is based on the habitat they invade. Holzner (1982) divided weeds into agrestals (weeds of agricultural systems, e.g. cereal/root crops, orchards, gardens, plantations), ruderals (weeds of waste/human disturbed sites), e.g. roadsides, railway lines, ditches e.g. *Alternanthera echinata*, *Tribulus terrestris*, grassland weeds (which include weeds of pasture, meadows, lawns), water weeds are those that affect water system (affect navigation, recreational use), forestry weeds (weeds of tree nurseries, afforestation sites) and environmental weeds (are those that suppress native vegetation). There is a tendency to use the word 'invasive' when considering natural habitats, and 'weed' for managed habitats; however, there is a gradient between natural and managed systems, and some apparently natural systems are managed (Holzner, 1982).

Effects of Weeds in the Environment

Weeds are perceived as valuable indicators of biodiversity because of their role in providing food or shelter for animal species. Much of the

decline in farmland birds has been linked to the reduction of weed occurrence in arable crops. Weeds provide habitat for game birds and other desirable wildlife species (Chandrasena, 2021). The rarer farmland birds can be encouraged to visit and to breed by accepting a certain level of weeds in a crop (Marshall *et al.*, 2003). Weedy strips are planted to encourage cover for game birds. While birds are particularly prominent and well recorded, the same arguments can be used for other, less well-studied organisms.

There is considerable interest in limiting weed management measures to allow populations of beneficial organisms to develop. Insects which pollinate crops (e.g. bumblebees) need a source of nectar and pollen when the crop is not in flower, and weeds can provide this. The natural predators of aphids include ground beetles, spiders and hoverfly larvae. Weed flowers may provide a food source for these natural predators and thereby reduce the reliance on aphicides (Serée *et al.*, 2023) or the weeds may be more attractive to crop pests. Certain weeds may limit insect damage to crops by interfering with pest movement or by providing habitat for natural enemies of pests (Nicholls and Altieri, 2018; Kleiman *et al.*, 2021).

Weed species can act directly as alternate food sources for phytophagous insects on which beneficial insects feed, or modify the microenvironment, allowing survival of beneficial natural enemies during adverse conditions (Norris and Kogan, 2000; Norris *et al.*, 2003). Within a field, evidence also suggests that some weeds can serve as alternative hosts of nematodes or protect nematodes from pesticides and the environment (Thomas *et al.*, 2005). Generally, weeds serve as alternative hosts to fungal and bacterial pathogens e.g. blast of rice, blight and rusts of maize. However, certain weeds can also provide nematode suppression through antagonism, contribute to changes in nematode biotic potential, or exert indirect effects on nematodes through competition with crops (Thomas *et al.*, 2005).

Weeds may also have beneficial properties such as erosion control. In natural ecosystems, the vegetative cover of a forest or grassland helps prevent soil erosion, replenish ground water and control flooding by enhancing infiltration and reducing water runoff (Lenka *et al.*, 2017). Bare soil is very vulnerable to erosion by wind and water. The presence of a plant cover helps to lessen the momentum of impacting raindrops and the plant roots help to bind the soil to reduce its ability to move. Non-native weeds can also be beneficial in non-agricultural situations, especially when the environment has been degraded (Lenka *et al.*, 2017).

Around the world, many wild plants are used as herbs for flavouring, sources of fodder and others are used for their medicinal properties (Table 1) (Lachman-White, 1992; Ajao *et al.*, 2022). There is a resurgence of interest in 'herbal' remedies which are perceived as safer than synthesized pharmaceutical drugs even though the latter have undergone a rigid approval process. Many drugs have their origins in plant secondary metabolites, and indeed some are still derived by extraction from plantings of such medicinal plants. *Chromolaena odorata* in tropical Africa has acquired a reputation as a medicinal herb for a variety of ailments including malaria, dysentery, toothache, diarrhoea, diabetes, skin diseases, fever and wound dressing (Phan *et al.*, 2001; Akinmoladun and Akinloye, 2007). The entire range of the domestic crops used in world agriculture is derived from wild species that have been modified through domestication, selective breeding and

hybridization. Most remaining world centers of diversity contain populations of variable and adaptable landraces as well as wild and weedy relatives of crops, all of which provide valuable genetic resources for crop improvement.

Toxicants or irritants produced by weeds can cause serious health problems for some people (Radosevich *et al.*, 2007). These discomforts or illnesses include hay fever, dermatitis and direct poisoning. Hay fever afflicts millions of people each year. It is caused by an adverse effect of proteins associated with the pollen of certain plants on the respiratory system of susceptible people (Speranza and Scoccianti, 2012).

Ragweed (*Ambrosia* spp.) is best known for causing hay fever (Knolmajer *et al.*, 2024). However, pollen from many other broadleaved plants, grasses, trees, and shrubs cause similar allergic reactions. Each year, many people are troubled by poison ivy (*Rhus radicans*), poison oak (*R. diversiloba*), and poison sumac (*R. vernix*) (Radosevich *et al.*, 2007). These plants produce and store a toxic substance called urushiol that causes intense itching and rash upon contact with the skin. Many plants contain toxic substances that when ingested cause sickness or death to humans. Toxic substances in weeds include alkaloids, glycosides, oxalates, resins and resinoids, volatile oils, acrid juices, phytotoxins (toxalbumens), and minerals (Radosevich *et al.*, 2007).

Mechanism of Weed Control in the Environment

Many of the methods and tools used to control, contain, or eradicate weeds and invasive plants are centuries old, while others have only been developed during the last several decades. In general, the approaches (methods and tools) used to reduce the abundance or vigor of unwanted vegetation vary only slightly according to habitat, that is, whether they are used in agriculture, other natural resource production systems like rangeland or forest plantations, or natural ecosystems. The tools used for weed control are categorized as physical, cultural, biological, or chemical method (Table 2). Reliance on a single tactic, particularly herbicides, has proven unsustainable due to resistance evolution and environmental concerns (Shaner and Beckie, 2014; Zimdahl, 2018).

Physical methods of weed control

Physical methods of weed control include any technique that uproots, buries, cuts, smothers, or burns vegetation. These methods consist of hand pulling and hoeing, fire, flame, tillage, mowing and shredding, chaining and dredging, flooding, and mulches and solarization.

Hand pulling and hoeing are the oldest most primitive forms yet effective weed control technique especially for smallholder farms. They are most effective on annual or simple perennial plants that are not able to sprout from roots or other vegetative organs. However, they are highly labor-intensive, with estimates of 150 h ha⁻¹ for corn, 165 h ha⁻¹ for cotton, and up to 516 h ha⁻¹ for spinach (Gianessi and Reigner, 2007; Abouziena and Haggag, 2016). Mechanical cultivation using tractors or inter-row cultivators reduces labor demands and can suppress annual weeds by severing shoots from roots, burying seedlings, or exposing them to desiccation. Nevertheless, poorly timed cultivation may inadvertently stimulate weed germination by bringing buried seeds to the soil surface (Zimdahl, 2018).

Table 1: Common spontaneous plants in the environment and their uses

S/N	Name	Habit	Uses	References
Amaranthaceae				
1	<i>Alternanthera sessilis</i> (L.) R.Br. ex DC.	Annual herb	Medicinal (boil, snakebite, astringent, headache, diarrhoea)	Ajao <i>et al.</i> , 2022
2	<i>Amaranthus viridis</i> L.	Annual herb	Food (vegetable); medicinal (hemorrhoid, blood tonic)	Ajao <i>et al.</i> , 2022
3	<i>Amaranthus spinosus</i> L.	Annual herb	Antipyretic, laxative, diuretic, anti-diabetic, anti-snake venom, analgesic, jaundice treatment	Kumar <i>et al.</i> , 2014
4	<i>Gomphrena celosoides</i> Mart.	Perennial herb	Medicinal (Skin and worm infections, induce abortion)	Ajao <i>et al.</i> , 2022
Asteraceae				
5	<i>Chromolaena odorata</i> (L.) R. M. King & H. Rob.	Perennial shrub	Medicinal (fever, toothache, skin disease, diarrhoea, headache, hemorrhoid, and fresh wounds)	Ajao <i>et al.</i> , 2022
6	<i>Eleutheranthera ruderalis</i> (Sw.) Sch.Bip.	Annual herb	Medicinal (Enhance milk production in lactating mothers and lower high blood pressure)	Lachman-White, 1992
7	<i>Spilanthes filicaulis</i> (Schumach. & Thonn.) C. D. Adams	Annual herb	Medicinal (Guinea worm infections)	Ajao <i>et al.</i> , 2022
8	<i>Synedrella nodiflora</i> (L.) Gaertn.	Annual herb	Medicinal (sores, skin infections)	Ajao <i>et al.</i> , 2022
	<i>Tridax procumbens</i> L.	Annual herb	Medicinal (antipyretic, hemostatic, back ache, stomach ache)	Beck <i>et al.</i> , 2018
Cucurbitaceae				
9	<i>Momordica charantia</i> L.	Perennial herb	Medicinal (malaria, fevers)	Lachman-White, 1992
Cyperaceae				
10	<i>Kyllinga pumila</i> Michaux	Perennial sedge	Food (condiment, spices, masticatories)	Burkill, 1985
11	<i>Mariscus flabelliformis</i> Kunth	Perennial sedge	Food (spice)	Ajao <i>et al.</i> , 2022
Euphorbiaceae				
12	<i>Euphorbia heterophylla</i> L.	Annual herb	Medicinal (skin infections, purgative)	Ajao <i>et al.</i> , 2022
13	<i>Euphorbia hirta</i> L.	Annual herb	Medicine (colds, flatulence)	Lachman-White, 1992
14	<i>Phyllanthus amarus</i> Schumach. & Thonn.	Annual herb	Medicinal (dysentery, blood purifier (bitter tonic), blood-sugar level)	Lachman-White, 1992
Fabaceae				
15	<i>Centrosema pubescens</i> Benth	Perennial herb	Medicinal (skin disease); Food for rabbit and goat	Ajao <i>et al.</i> , 2022
16	<i>Senna hirsuta</i> (L.) H.S. Irwin & Barneby	Perennial shrub	Medicinal (skin infection, purgative)	Ajao <i>et al.</i> , 2022
17	<i>Mimosa pudica</i> L.	Perennial herb	Medicinal (fibroid, deworming, hemorrhoid)	Ajao <i>et al.</i> , 2022
Lamiaceae				
18	<i>Solenostemon monostachyus</i> (P. Beauv) Briq.; H	Annual Herb	Medicinal (convulsion, stomachache, diabetes)	Ajao <i>et al.</i> , 2022
19	<i>Hyptis suaveolens</i> (L.) Poit.	Annual herb	Insecticide (mosquito repellent)	Lachman-White, 1992
Loganiaceae				
20	<i>Spigelia anthelmia</i> L.	Annual herb	Hypertension and thrush	Lachman-White, 1992
Malvaceae				
21	<i>Corchorus olitorius</i> L.	Annual herb	Food (vegetable)	Maroyi, 2013
22	<i>Corchorus tridens</i> L.	Annual herb	Food (vegetable); medicinal (hemorrhoid, blood tonic)	Maroyi, 2013
23	<i>Sida acuta</i> Burm. f.	Perennial shrub	Medicine (abscesses)	Lachman-White, 1992
24	<i>Urena lobata</i> L.	Perennial shrub	Medicinal (dysentery, expectorant, emollient)	Ajao <i>et al.</i> , 2022
Piperaceae				
25	<i>Peperomia pellucida</i> (L.) H.B & K	Annual herb	Medicinal (Eye infections, hypertension, heart troubles)	Lachman-White, 1992
Poaceae				
26	<i>Cynodon dactylon</i> (L.) Pers	Grass	Medicinal (diarrhea, biliousness, itching)	Lachman-White, 1992
27	<i>Eleusine indica</i> Gaertn	Annual grass	Medicinal (wounds)	Lachman-White, 1992
Portulacaceae				
28	<i>Portulaca oleracea</i> L.	Annual herb	Medicinal (fever, skin disease, astringent, diabetes)	Ajao <i>et al.</i> , 2022
29	<i>Talinum triangulare</i> (Jacq.) Willd.	Herb	Food (vegetable); medicinal (boil, high fever, hemorrhoid, HBP, blood supplement)	Ajao <i>et al.</i> , 2022
Rubiaceae				
30	<i>Mitracarpus villosus</i> (Sw.) DC.	Annual herb	Medicinal (skin infections)	Ajao <i>et al.</i> , 2022
Solanaceae				
31	<i>Physalis angulate</i> L.	Annual herb	Medicinal (fever, malaria, female infertility, stomach upset)	Lachman-White, 1992; Ajao <i>et al.</i> , 2022
32	<i>Datura metel</i> L.		Medicinal (Asthma, rheumatism); Stimulant	Ajao <i>et al.</i> , 2022
Urticaceae				
33	<i>Laportea aestuans</i> (L.) Chew	Annual herb	Medicinal (diuretic, laxative and eye-wash)	Lachman-White, 1992
Verbenaceae				
34	<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	Perennial shrub	Medicinal (hypertension, thrush, eye infection)	Lachman-White, 1992

Table 2: The mechanism of weed control

Method	Examples	Strengths	Limitations
Physical	Hand pulling, hoeing, fire, tillage, mowing	Immediate removal, low cost	Labor-intensive, short-term
Cultural	Crop rotation, cover crops, canopy manipulation	Preventive, improves soil health	Requires planning, slower impact
Biological	Grazing, bioherbicides, allelopathy	Sustainable, eco-friendly	Slow action, variable success
Chemical	Herbicides (sulphates, nitrates)	Fast, effective	Resistance, environmental concerns

Fire is another tool that has been available to humans for centuries for the manipulation of vegetation. It is still used extensively to remove vegetation and crop residues in agriculture and to prepare forest lands for regeneration after clear-cut logging. Muyt (2001) observed that fire can be an effective weed management tool in certain natural ecosystems when applied carefully and selectively. Muyt (2001) indicated that fire is used for various management purposes, including destroying mature plants and eliminating seedlings, exhausting weed seed banks, improving access for follow-up treatments and encouraging regrowth, removing dried weed material, stimulating germination, growth, and spread of indigenous vegetation. Tillage or cultivation is disturbance of the soil. A major benefit of tillage is prevention and suppression of weeds. Tillage suppresses weeds by breaking, cutting, or tearing them from the soil, thus exposing the vegetation to desiccation, and by smothering them with soil.

Mowing is used to control weeds by cutting or shredding their foliage. In some situations, it is desirable to decrease the amount of vegetation that is already present without killing it. Power line rights-of-way (pathways or property where transmission powerlines are located), some roadsides, ditch banks, abandoned cropland, or vacant lots are areas where weeds are mowed periodically. Mowing can suppress some perennial weeds through carbohydrate starvation and altering the stature of some weeds (Abouziena and Haggag, 2016). A common morphological response of plants that have been mowed is to regenerate several new shoots from below the cut.

Chaining and dredging are used to control weeds in the aquatic environments. While chaining removes floating aquatic weeds with the help of a heavy chain, dredging removes weeds along with their roots and rhizomes with the help of mechanical force. Soil solarization referred to the solar heating of the soil. Soil solarization with black polythene showed the highest weed control efficiency of 85.84%, indicating its suitability for use in weed control (Shinde *et al.*, 2023). Nwagwu *et al.* (2022) reported that white polyethylene was more effective in weed suppression and resulted in heavier 1000-grain weight of maize compared with green and black polyethylene. On a two-year average, soil solarization for 6, 4, and 2 weeks before planting reduced weed density by 81.03%, 59.26%, and 30.47%, and weed dry matter by 76.61%, 66.21%, and 29.97%, respectively, compared with the control (no solarization) (Nwagwu *et al.*, 2022).

Tillage remains a cornerstone of mechanical weed control. Primary tillage buries weed seeds and seedlings, while secondary tillage disrupts emerging weeds. The timing and depth of tillage are critical: deep plowing can reduce surface germination of light-sensitive seeds, whereas shallow disking may increase weed emergence by exposing seeds to favorable conditions (Zimdahl, 2018). Conservation tillage

systems, while beneficial for soil health, often reduce mechanical suppression opportunities, necessitating integration with other methods (Shaner and Beckie, 2014).

Cultural methods of weed control

Cultural methods of weed control involve processes (weed prevention, crop rotation, crop competition, smother crops, living mulches and cover crops, and harvesting operations) (Radosevich *et al.*, 2007) that manipulate cropping systems and agronomic practices to suppress weed growth and reproduction. Cultural strategies aim to create conditions that favor crop competitiveness while disfavoring weeds. These methods are central to integrated weed management (IWM), particularly in organic and low-input systems, and are often considered more sustainable due to their preventive nature and compatibility with ecological principles (Zimdahl, 2018).

Weed prevention involves procedures that inhibit or delay establishment of weeds in areas that are not already inhabited by them. These practices restrict the introduction, propagation, and spread of weeds on a local or regional level. The prevention or quarantine of a weed problem is usually easier and less costly than control or eradication attempts that follow weed introductions because weeds are most tenacious and difficult to control after they become established.

Crop rotation disrupts weed life cycles by alternating crops with different growth habits, planting dates, and resource requirements. Rotations that include winter cereals, legumes, or cover crops reduce the dominance of summer annual weeds and deplete seedbanks over time (Abouziena and Haggag, 2016). Adjusting planting dates can also exploit phenological mismatches; for example, early sowing of maize can outcompete warm-season weeds such as nutsedge (Zimdahl, 2018). As weed vigour is influenced by crop abundance, size, and proximity (Mohler, 2001), the use of competitive cultivars with traits such as rapid early growth, greater height, and early canopy closure enhances crop suppression of weeds. Therefore, cultural practices that shift the balance of competition toward the crop will usually disfavor weed occurrence and improve crop yields. Plant canopy cover can be used to reduce weed abundance by manipulating the conditions that weed seed require to either germinate or remain dormant. Plant canopies can be manipulated to suppress weeds by the density and arrangement of the desirable plants, whether they are agricultural crops, forest trees, or native species planted for restoration of an invaded site (Quinn, 2006).

Cover crops such as rye (*Secale cereale* L.) and legumes (e.g., clover, vetch) suppress weeds through physical shading, allelopathic effects, and resource competition. Living mulches and companion cropping provide continuous ground cover, reducing opportunities for weed establishment (Zimdahl, 2018). These practices also improve soil

fertility and structure, contributing to long-term sustainability. However, careful management is required to avoid competition between cover crops and the main crop.

Stale seedbed techniques involve preparing the soil weeks before planting to stimulate weed germination, followed by shallow cultivation or flame weeding to eliminate seedlings before crop sowing. This reduces weed pressure during the critical early stages of crop growth (Abouziena and Haggag, 2016). While effective, stale seedbeds may delay planting and require precise timing to avoid yield penalties. Manipulating fertilizer placement and timing can favor crops over weeds. Precision fertilizer management, including banding nutrients near crop rows, reduces availability to interrow weeds (Shaner and Beckie, 2014). Similarly, irrigation scheduling can be adjusted to benefit crops while limiting weed proliferation, particularly in water limited environments.

Biological methods of weed control

Biological methods of weed control involve the use of living organisms to lower the population or competitive ability of weed species so it is no longer an economic problem. Biological control differs from other methods of weed control in several ways as stated by Rosenthal *et al.* (1989). It does not necessarily kill the weed outright; instead, often only the competitive or reproductive ability of the affected plant is reduced and it may be slow-acting, often requiring years to achieve acceptable control levels. Thus, biological control should not be attempted when the destruction of the weed is needed immediately. It is also relatively inexpensive, especially in contrast to the high costs of development (and frequent use) of herbicides.

Grazing is perhaps the oldest and most common form of biological weed control. It can be accomplished using a wide array of animals that eat vegetation, including large ruminants and ungulates, birds, insects, and fish. This approach is particularly effective in rangeland and pasture systems, where selective grazing suppresses undesirable species while maintaining forage quality (Zimdahl, 2018). Plant pathogens have also been used effectively to control weeds in augmentative-type biological control programme because plant pathogens are easily and cheaply cultured on artificial media. An organism used in this manner has been termed a bioherbicide or if the organism is a fungus a mycoherbicide. Cruttwell (2000) indicated that three invasive plants namely, northern joint vetch (*Aeschynomene virginica*), milkweed vine (*Morrenia odorata*), and broomrape (*Orobancha ramosa*), have been controlled successfully by fungi applied as mycoherbicides.

Allelopathy is any direct or indirect effect of one plant on another through the production and release of secondary chemicals into the soil rhizosphere. Allelochemicals are present in all types of plants and tissues and are released by a variety of mechanisms including decomposition of plant residues (shoot or root), root exudation, and volatilization (Weston, 2005). Allelopathic interactions may inhibit the germination or growth of neighboring species. Cover crops such as rye (*Secale cereale* L.) and legumes release allelopathic compounds that suppress small-seeded annual weeds (Shaner and Beckie, 2014). Incorporating allelopathic species into rotations or as living mulches enhances crop competitiveness and reduces reliance on herbicides

Chemical methods of weed control

Chemicals, like other methods of weed control, have been used for centuries to suppress or remove weeds (Kraehmer *et al.*, 2014). Crafts (1975) indicated that solutions of sodium nitrate, ammonium sulphate, iron sulphate, and sulphuric acid were all effective treatments for weed control in cereal crops by 1900. The use of these chemicals for weed control expanded rapidly during the middle portion of the twentieth century, following the discovery of several synthetic organic substances that killed or suppressed vegetation. While there are records of ancient civilizations using chemicals such as common salt and wood ashes to control unwanted vegetation (Green *et al.*, 1987; Matthews, 2018), the widespread use of herbicides is a very recent phenomenon that did not become a significant factor in crop production until the 1950s (Matthews, 2018; Casimero *et al.*, 2022). Herbicidal oils and dinitrophenolic compounds were among the first organic chemicals to be used for weed control. However, it was the discovery of the plant-growth-suppressing ability of 2, 4-D shortly after World War II that led to the expansive growth of chemical tools for weed control (Casimero *et al.*, 2022).

Herbicides

Herbicides are organic or synthetic chemicals used to kill or suppress unwanted vegetation. They represent an extremely broad array of chemical classes and, in turn, act at a large number of sites of metabolic function and energy transfer in plant cells. To be effective, herbicides must adequately contact plants, be absorbed by plants, move within the plants to the site of action without being deactivated, and reach toxic levels at the site of action.

Although herbicides are easy to buy from the market, easy to use, decrease the need for a large labour force, and allow for quick yield, many adverse health effects and environmental impacts have resulted from their use (Bulu *et al.*, 2017; Bulu, 2018). Herbicides not only destroy targeted weeds, but also contaminate soil, water, and air thereby damaging the surrounding and remote ecosystems and other living organisms necessary for maintaining ecological balance, such as, insects, birds, worms and fish (Siriwong *et al.*, 2008; 2009).

Classification of herbicides based on mode and time of application

Herbicides can be classified based on the time of application, either before weeds sprout or after sprouting (Vats, 2014). A pre-emergent herbicide is applied before weeds sprout or emergence of weed seedling while a post-emergent herbicide is applied after sprouting of weeds. Selection of a post-emergent herbicide may depend on crop age, rate applied or other factors.

Herbicide may be classified as systemic or contact (Vats, 2014). Most herbicides are systemic, which means they move from the point of initial absorption to other parts of the plant. They may be sprayed on the leaves and move to the roots or vice versa. These products circulate through the plant to have their effect.

Contact or non-systemic herbicides affect only the part of the plant they touch (Vats, 2014). Thus, they may control young annual or biennial weeds, but established perennial weeds that lose leaves due to a contact herbicide application will re-sprout. Products containing soap, clove oil and vinegar act as contact herbicides (Win *et al.*, 2023). They are most effective on annual weeds when they are young.

Herbicide selectivity refers to the differential tolerance of plant species to a given herbicide dose, where some survive while others are lethally affected (Crafts, 1946; Sherwani *et al.*, 2015; Chipomho *et al.*, 2023). Selective herbicides act specifically on target weeds by absorption and translocation through the xylem or phloem, disrupting metabolic or biosynthetic pathways and ultimately causing plant death (Fernandez and Brown, 2013). In contrast, nonselective herbicides are broad-spectrum agents that destroy nearly all vegetation, including grasses, broadleaf weeds, and crops (Sherwani *et al.*, 2015; Chipomho *et al.*, 2023). Their primary use is in total vegetation control, such as on driveways or fence lines and mainly as pre-planting treatments in agriculture.

Herbicide selectivity is influenced by multiple factors, including plant physiology, soil characteristics, environmental conditions, application timing, dosage, and technique (Sherwani *et al.*, 2015). Common active ingredients include glyphosate, glufosinate ammonium, and paraquat (Chipomho *et al.*, 2023).

Herbicides also are classified by the way they move into plants. Many common herbicides brands are foliar-active, which enter through the leaves of plants. For example, glyphosate (Roundup) enters through green tissue. Soil-active herbicide brands are however applied to the soil and are absorbed through roots or through the growing tips of germinating seeds. Some herbicide brands are both soil and foliar-active, although one absorption route usually is more important.

Classification of herbicides based on mode of action

Herbicides are grouped into families based on their mode of action which is the characteristic way they affect plants or categorized into groups based on their active ingredients.

Growth regulator herbicides

These herbicides are widely used to control broadleaf weeds (Gunsolus and Curran, 1991; Armstrong, 2009). Growth regulator herbicides or synthetic auxin upset the normal hormonal balance that regulates processes such as cell division, cell enlargement, protein synthesis, and respiration. They are usually applied to the foliage, but are also effective in the soil (Gunsolus and Curran, 1991). Herbicides in this category include phenoxy growth regulator herbicides which have the least plant activity and soil residual activity, the benzoic acids and the pyridines (Gunsolus and Curran, 1991). The most common symptoms for these herbicides are leaf (cupping, crinkling, parallel veins, leaf strapping) and stem malformations (stem twisting (epinasty), callus tissue formation) (Gunsolus and Curran, 1991). Examples of growth regulator herbicides include 2,4-D, Dicamba, Triclopyr, Clopyralid, Picloram.

Photosynthesis inhibitor herbicides

Herbicides in this category inhibit the process of photosynthesis pathway, (the process by which all green plants convert light energy from the sun into sugars (food)) specifically the Photosystem II (PSII) (Sherwani *et al.*, 2015) and Photosystem I (Armstrong, 2009). Photosynthesis inhibitors are broad-leaf herbicides, but they also control annual grasses to some extent. Some of these herbicides such as Buctril® and Tough® are used as foliar, selective, post-emergence products. Others such as atrazine are generally used as pre-emergence

sometimes as post-emergence herbicides. Other herbicides in this family include the triazinone, triazine, uracil, urea, amide and nitrile herbicides (Gunsolus and Curran, 1991; Dallas *et al.*, 2013).

In addition to the effects of starvation for photosynthate, sunlight-induced secondary reactions can cause photooxidation of chlorophyll, resulting in contact-like herbicide symptoms and more rapid destruction of plant tissue than is caused by simple starvation. The most common symptom produced by photosynthesis inhibitors in susceptible plants is chlorosis (yellowing) of the leaf tissue (Gunsolus and Curran, 1991). In grasses, symptoms first appear on the older leaves near the base of the plant. Leaf tips and margins first show chlorosis and eventually turn necrotic. In broadleaves, the oldest leaves are affected first and show chlorosis of leaf margins and interveinal tissue, followed by necrosis. Symptoms depend on the product's mobility within the plant. Herbicides in the triazine, triazone, uracil and urea families move within the plant and exhibit these symptoms in older leaves first: yellowing between the leaf veins or in the veins; and yellowing of the leaf margins that eventually turn brown and die (Gunsolus and Curran, 1991). Herbicides in the benzothiadiazole, nitrile, phenyl-pyridazine and amide families are not mobile within the plant and affect only treated leaves. Symptoms include speckling, spotting, and yellowing or bronzing that may kill affected tissues (Gunsolus and Curran, 1991).

Pigment inhibitor herbicides

Herbicides classified as pigment inhibitor destroy the green pigment (chlorophyll) which is essential for photosynthesis in leaf tissue (Gunsolus and Curran, 1991; Sherwani *et al.*, 2015). These herbicides are absorbed by roots and translocated to the shoot tissue where they inhibit the production of carotenoids-substances that protect the chlorophyll molecules that make plants green. The families present are the isoxazol, pyridazinone and the triazole. Injured leaves turn yellow or white, then translucent while new growth is yellow to white with sometimes a tinge of purple or pink (Sherwani *et al.*, 2015). These symptoms can be found on cotyledons to the newest leaves of susceptible plants.

Seedling growth inhibitor herbicides

Some herbicides act on seedling weeds shortly after they germinate and before they emerge. These herbicides work beneath the soil so their effects are seldom seen. If over-applied, however, they may inhibit growth of weed or crop seedlings that do emerge through the soil surface. These herbicides can be divided into two groups-root inhibitors and shoot inhibitors.

Root inhibitor herbicides interrupt cell division, which stops root growth in seedling weeds (Gunsolus and Curran, 1991). This group is represented by the benzamide, benzoic acid [dimethyl-2,3,5,6-tetrachloroterephthalate (DCPA), dinitroaniline, phosphoramidate, and pyridine chemical family, which act by causing the loss of microtubule formation leading to the obstruction of cell division and elongation as evidenced by the swelling of the root tips (Sherwani *et al.*, 2015). They are most effective on small-seeded broadleaf and grass weeds. Large-seeded weeds and crops generally survive normal dosages because their roots and shoots grow through the herbicide-treated zone in the soil. Injury to tolerant plants is caused by root damage. Grass crops may be stunted and have a purple discoloration because roots cannot take up

enough phosphorus. Root systems especially the lateral roots appear stubby and thick (Gunsolus and Curran, 1991).

The seedling shoot growth inhibitor, represented by the chemical family chloroacetamide, acetamide, oxyacetamide, and tetrazolinone, acts on newly germinated weed seeds. These herbicides bind to acetyl-CoA and certain sulfur-containing molecules through thiocarbamate sulfoxides and block the formation of long-chain fatty acids, stopping seedling shoots from growing and preventing weeds from emerging (Sherwani et al., 2015). They are most effective at controlling small-seeded grass and broad-leaf weeds. Symptoms include leafing out underground, improper leaf unfurling, tightly-rolled leaves, and leaf crinkling. In broadleaf plants, the center vein (mid-rib) may draw in the leaf edge in a draw-string effect. Leaf puckering is also a symptom on broad-leaf plants (Dallas *et al.*, 2013).

Cell membrane disruptor herbicides

The cell membrane disruptor post-emergence herbicides control both grasses and broadleaf weeds by destroying cell membranes and causing rapid desiccation of the plant. There are two types of cell membrane disruptor herbicides, the bipyridiliums (paraquat, difenzoquat) and the diphenylethers (acifluorfen, lactofen, fomesafen) (Gunsolus and Curran, 1991). The bipyridilium herbicides require thorough plant coverage to be effective, and they have no soil activity. The diphenylether herbicides act in a similar way but more slowly. Plants rapidly turn yellow or pale and may look water-soaked, then they dry up (Gunsolus and Curran, 1991). The effects of the bipyridilium herbicides are rapid. Even small droplets that drift to non-target vegetation cause specks of burned tissue. Roots of perennial weeds are seldom killed because these herbicides do not usually translocate to the roots (Dallas *et al.*, 2013).

Lipid synthesis inhibitor herbicides

Lipid synthesis inhibitors selectively target annual and perennial grasses (Gunsolus and Curran, 1991). Lipids, primarily fatty acids, are essential for normal plant function as they form cellular membranes that regulate transport processes. By blocking fatty acid biosynthesis, these herbicides prevent membrane formation, leading to growth inhibition. They are rapidly absorbed through leaves and become rainfast within one hour. Two major classes of lipid biosynthesis inhibitors are cyclohexanediones and aryloxyphenoxypropionates (Duke, 1990). Symptoms develop slowly on grass plants and may not appear for 7 to 14 days. Initial injury is seen where the newest leaves are developing. These regions usually turn pale or yellow and then die. The area at the base of new leaves quickly becomes mushy, has a rotted appearance, and new leaves in the affected area can be pulled easily from the rest of the plant (Gunsolus and Curran, 1991).

Amino acid synthesis inhibitor herbicides

These herbicides can be used at extremely low rates to control both grasses and broadleaf plants. They bind to a specific enzyme and prevent the development of amino acids essential to plant life. The enzyme to which they bind is known as Acetolactate synthase (ALS). Families of herbicides in this category include the imidazolinone, sulfonyleurea, triazolopyrimidine and the pyrimidinylthio-benzoate (Gunsolus and Curran, 1991). Symptoms for grasses include stunting, purple coloration, and root systems that develop a “bottlebrush” appearance. On broad-leaf plants, symptoms include red or purple leaf

veins, yellowing of new leaf tissue, and sometimes blackened terminals (Gunsolus and Curran, 1991).

Some other herbicides also affect amino acid synthesis but in a different way to the previous group. These herbicides are non-selective and control a broad range of annual and perennial grasses, broadleaves and sedges. Common herbicides in this category are glyphosate, glufosinate and sulfosate

Integrated Weed Management (IWM)

Integrated Weed Management (IWM) (Figure 2) is a holistic approach that combines the diverse weed control strategies (physical, biological, selective herbicide use) to achieve sustainable suppression of weed populations while maintaining crop productivity and environmental integrity (Abouzienna and Haggag, 2016; Shaner and Beckie, 2014). The principles of IWM emphasize diversification, ecological understanding, long-term sustainability, and environmental protection. Effective IWM requires consideration of weed biology, crop-weed competition and exploiting ecological weaknesses of weeds to reduce their persistence (Zimdahl, 2018). By reducing herbicide dependence, IWM minimizes chemical residues in soil and water. Integrated Weed Management offers several advantages that make it a valuable approach in modern agriculture. By relying on diversified tactics rather than a single method, IWM helps slow the evolution of herbicide-resistant weeds, ensuring that chemical controls remain effective for longer periods. It also promotes economic efficiency, since combining different strategies reduces long-term costs compared to heavy dependence on herbicides or the labor-intensive practice of hand weeding. Beyond financial benefits, IWM contributes to environmental sustainability by lowering chemical inputs, which in turn reduces pollution and safeguards biodiversity. Finally, it supports yield stability, as maintaining low weed densities helps protect crop productivity consistently across seasons.

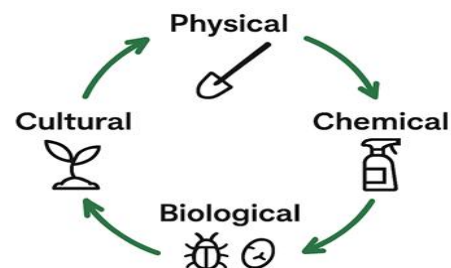


Fig 2: Integrated weed management

Despite its benefits, IWM faces challenges. The complexity of planning requires detailed knowledge of weed biology, cropping systems, and integration of multiple practices. Adoption barriers include perceived costs, time demands, and lack of immediate results, which may discourage farmers (Shaner and Beckie, 2014). In addition, technology gaps, such as the need for robust weed recognition systems and affordable precision implements, limit widespread adoption (Christensen *et al.*, 2009).

Future Outlook on Weed Control

Diversification and Sustainability

The future of weed control will be defined by diversification, technological innovation, and sustainability. Reliance on herbicides alone has proven unsustainable due to the rapid evolution of herbicide-resistant (HR) weed populations and growing environmental

and public health concerns (Shaner and Beckie, 2014). Moving forward, IWM systems that combine cultural, mechanical, biological, and chemical approaches will be essential.

Precision and Digital Agriculture

Site-specific weed control technologies, including advanced weed sensing systems, decision support models, and precision implements, are expected to play a central role in future weed management (Christensen *et al.*, 2009). Machine vision, artificial intelligence, and drone-based mapping will enable real-time identification and targeted treatment of weed patches or individual plants, reducing herbicide inputs by up to 90% while minimizing crop injury. Integration of these technologies into precision agriculture frameworks will allow growers to tailor interventions to local weed populations and environmental conditions.

Novel Chemical and Biological Tools

The discovery of new herbicide modes of action has slowed dramatically, with no major introductions in over two decades (Shaner and Beckie, 2014). Future chemical innovations may include metabolism-based classifications, synergists that inhibit detoxification pathways, and RNA interference technologies to silence resistance genes. Biological approaches, such as mycoherbicides, allelopathic cover crops, and microbial biocontrol agents, will complement chemical tools, particularly in organic and low-input systems (Abouziena and Haggag, 2016).

Cultural and Preventive Strategies

Preventive measures, including clean seed, crop rotation, competitive cultivars, and cover crops, will remain foundational in weed management. Zimdahl (2018) emphasized that prevention is the most cost-effective long-term strategy, though difficult to measure. Future systems will increasingly integrate preventive cultural practices with digital monitoring to reduce seedbank replenishment and slow resistance evolution.

Policy and Societal Drivers

Public acceptance of chemical weed control and genetically modified crops will continue to shape regulatory frameworks. Stricter pesticide regulations in Europe have already reduced available herbicide options by more than 60% between 1999 and 2009 (Shaner and Beckie, 2014). Policies that incentivize stewardship, conservation tillage, and diversified rotations will be critical to align grower practices with sustainability goals. Global collaboration and multidisciplinary research will be necessary to address resistance management and ensure food security.

Conclusion

Weed management remains one of the most critical challenges in global agriculture, as weeds consistently cause greater yield losses than any other pest group. The evidence reviewed demonstrates that no single method, mechanical, cultural, biological, or chemical, can provide sustainable long-term control. Mechanical approaches deliver immediate suppression but are often labor-intensive; cultural practices strengthen crop competitiveness and reduce seedbank replenishment; biological methods offer environmentally friendly alternatives yet require further refinement; and chemical herbicides, while indispensable, must be applied judiciously to prevent the rapid evolution of resistance.

Against this backdrop, IWM emerges as the most viable pathway toward sustainable weed control. By strategically combining preventive cultural practices, mechanical suppression, biological innovations, and cautious chemical use, IWM reduces reliance on herbicides, delays resistance development, and enhances environmental stewardship. Although more complex to implement than single-method approaches, IWM provides long-term profitability and resilience, making it particularly relevant for modern agricultural systems facing both economic and ecological pressures.

The future of weed control lies in diversified, technology-enabled systems that integrate cultural practices with precision mechanical and chemical interventions, biological innovations, and supportive policy frameworks. Advances in site-specific technologies, digital agriculture, and novel biocontrol tools will further enhance efficiency and sustainability. Importantly, weeds should not be viewed solely as undesirable plants; their persistence reflects ecological strategies such as seedbank longevity, reproductive plasticity, and competitive interactions with crops. Moreover, weeds can contribute ecological services, including biodiversity support, erosion control, and medicinal resources. Effective management must therefore balance the need to minimize negative impacts with recognition of potential benefits.

Future research should prioritize innovations such as remote sensing, machine learning for weed detection, and bioherbicides to improve precision and reduce dependence on synthetic chemicals. Ultimately, a deeper understanding of weed ecology in its full complexity is essential for designing resilient agricultural systems that safeguard productivity while conserving ecological integrity.

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The author declares no conflicts of interest

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Ethics Approval

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