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Meet the editor

Dr. Muhammad Aamir Iqbal (Ph.D.) is an academician and researcher in the discipline of Agronomy with research interest in sustainable crop production and soil management, genetic improvement of field crops, weed management and organic farming, plant nutrition and seed science, grasslands and watershed management and bioengineering based solutions of converting crop residues into valuable products. Dr. Iqbal is currently engaged as a Fulbright postdoctoral scientist at Louisiana Tech University, USA, and has a role in advancing scientific research on crop left-overs management and their conversion into marketable products using chemical engineering approaches. Previously, he has undergone intensive research training at the University of California Davis, USA, Shandong Academy of Agricultural Machinery Sciences, China, and Yunnan Sugarcane Research Institute, Kiyuan, China. Dr. Iqbal was conferred a doctorate degree in agronomy by a prestigious seat in agricultural learning and research in South Asia, University of Agriculture Faisalabad, Pakistan. To his credit, he has over 164 scientific publications and three dozen book chapters on diversified aspects of sustainable crop production and genetic improvement of field crops. Additionally, he has edited three books on different aspects of crop production, weed management, and grassland conservation. Dr. Iqbal is the editorial board member of many reputed high-impact journals and serves as a reviewer of over a dozen journals indexed by Web of Science (JCR) and Scopus. Being a member of the National Curriculum Revision Committee (NCRC) of Pakistan's Higher Education Commission (HEC), he has been involved in the critical task of revising and updating the curriculum of undergraduate and postgraduate degree programs offered by Pakistani HEIs (Higher Education Institutes) in the subjects of Agronomy and Crop Physiology. Dr. Iqbal is a faculty member in the Department of Agronomy, Faculty of Agriculture, University of Poonch Rawalakot, Azad Jammu and Kashmir, Pakistan, with responsibilities of teaching, research, research mentorship, administration, and outreach activities. Moreover, he has completed research projects as principal investigator and supervised the research of several postgraduate scholars.

Contents

Preface

A famous proverb signifies the complex challenges in agriculture: “Farming looks mighty easy when your plow is a pencil and you’re a thousand miles from the cornfield”. In modern agriculture, weed management has emerged as the foremost challenge hindering the achievement of potential productivity and nutritional quality of crops, efficient use of farm inputs (solar radiation, irrigation, fertilizers, etc.), economic turnouts of farmers, and ecosystem balance. Often, weeds are perceived as simple nuisances, however, these tend to impart far-reaching impacts on crop production, the economic viability of prevalent farming systems, the food security of the skyrocketing human population, the biodiversity of flora and fauna in terrestrial ecosystems, and environmental robustness. Recently, advancements in Agronomy (particularly weed science), Soil Science, Food Science, and Environmental Sciences have transformed prevalent weed management approaches, leading to the integration of traditional practices and evolving innovative strategies. Moreover, chemical engineering-based waste processing options have revealed the potential to transform weeds into wealth. However, these management strategies, when applied solely or in integration with each other, pose unique advantages and challenges.

This book, *Weed Management – Global Strategies*, offers a unique and comprehensive exploration of conventional approaches and recently developed innovative strategies to keep native and invasive weed species below threshold levels effectively and sustainably.

Additionally, this book strives to present a balanced literature on prevalent and established weed management strategies along with emerging approaches. The content is structured to benefit a wide readership, from students and researchers to agriculture and environmental science practitioners. The first section introduces the biology and ecology of weeds, laying a foundation for understanding their role in agricultural systems. The subsequent section delves into mechanical, chemical, biological, and cultural control methods, followed by a discussion of integrated weed management practices. Case studies and examples from various cropping systems illustrate these concepts, offering practical insights and real-world applications.

Chapter 1 introduces the fundamentals and advancement of different formulations of traditional herbicides such as solution, wettable powders, emulsions, emulsifiable concentrates, suspension concentrates, granules, water dispersible granules, oil-in-water, microemulsions, microcapsules, and suspo-emulsions that have been sources of toxicity in food supply chain and environmental pollution. Contrastingly, this chapter proposes that nano-herbicides contain nanoparticles aimed at improving the efficiency of the active chemical agents, accuracy of delivery to the targeted weed species, reducing the quantity of active ingredient needed, leading to a significant decline in potential negative impacts on crop plants, soil microbiota, water bodies, agricultural workers, food chain, and the environment.

Chapter 2 signifies that in southern states of the United States (US), particularly in Louisiana, noxious broadleaf weeds have become undesired flora that tends to dominate crop plants in all types of farming systems. By genotypic superiority-driven robust growth habits and unprecedented reproductive potential, weed species acquire more growth resources (moisture, nutrients, solar radiation, etc.) than crop plants. Considering changing climate scenarios and environmental pollution associated with the extensive use of herbicides, researchers have realized the need to explore and understand the remarkable agro-botanical superiority of weeds. Formulating and re-optimizing weed management approaches has become essential for improving farming practices. To attain these objectives, this chapter synthesizes fundamental knowledge on a few prevalent weeds (e.g., pigweed, alligator weed, Chinese tallow, and parthenium weed) of Louisiana. Moreover, the prevalence of invasive weed species in the region has been objectively analyzed, and an economically viable chemical engineering-based weed management strategy (hydrothermal carbonization) for converting weed biomass into organic soil amendment (hydrochar) has been proposed. Such an approach holds the potential to keep weeds below the threshold level and reduce the use of herbicides, along with imparting sustainability to common Louisiana farming systems.

Chapter 3 reports that weed management is an important challenge in all farming systems, but it is more complicated in organic farming due to the lack of chemical options. Concern about potential increases in weed populations without the use of herbicides has limited the uptake of organic farming even though organic products are gaining popularity among consumers. Different weed management strategies differ in their ability to control weeds and often have unique agroecological implications. The primary concern in an organic production system is how and when to adopt the management practices to make the system productive and profitable. Generally, an integrated management approach using organic herbicides and mechanical, cultural, and biological practices is considered best for weed control in organic systems.

Chapter 4 proposes that biological invasion is a global ecological problem, and it is important to understand the mechanism of successful invasion to prevent and control invasive weeds. Based on my experience and expertise in ecology, I have observed a significant gap in the literature regarding Compositae weeds invasions and aimed to address this gap. This chapter offers a comprehensive overview of the current state of knowledge in this field and presents a unique perspective incorporating existing theories. A clear address of the aggressive invasiveness of invasive species belonging to Compositae and the proposal of scientific prevention, control, and management strategies will help prevent future invasions around the world.

Chapter 5 highlights that the crop production sector faces the critical challenge of effectively managing weeds while reducing herbicide dependence, which aligns with environmental and economic sustainability. This chapter explores the shift toward site-specific weed management (SSWM), accelerated by artificial intelligence (AI) and digital technologies. Also, it addresses the often-neglected complexities of weed-seed bank germination. We propose an integrated approach, combining AI-enhanced weed detection, cover crop strategies to limit weed seedling emergence, cost-effective spot spraying, and the application of large language models to enrich decision-making under an integrated weed management (IWM) scheme. This helps ensure varied management tactics and weed resistance prevention.

Chapter 6 provides an overview of weed management in organic farming due to the lack of chemical options. Concerns about potential increases in weed populations without the use of herbicides have limited the uptake of organic farming, even though organic products are gaining popularity among consumers. Different weed management strategies differ in their ability to control weeds and often have unique agroecological implications. Broadleaf weeds, grasses and sedges are the three major classes of weeds impacting quality and yield in both horticultural and row crop systems. The major concern in an organic production system is how and when to adopt management practices to make the system productive and profitable. Generally, an integrated management approach using organic herbicides and mechanical, cultural, and biological practices is considered best for weed control in organic systems.

Chapter 7 focuses on pulses' significance as these provide an affordable source of dietary protein and other vital nutrients. However, various biotic (weeds, pathogens, and insect infestation) and abiotic (temperature, nutrient stress, waterlogging, drought, salinity, and heavy metals) constraints induce substantial harm by decreasing their production. Weeds pose a significant global challenge as they compete not only with crops for vital resources such as sunlight, space, nutrients, and water but also attract other pests and pathogens that can harm the pulse crops. The weed–crop intervention varies significantly based on the crop type, topography, and soil characteristics. Implementing chemical weed control strategies not only revolutionized global agriculture but was also widely acknowledged as an essential tool in accelerating crop productivity.

Key Features of the book:

- Furnishes fundamental and state-of-the-art knowledge on weed management using artificial intelligence tools.
- Presents integrated strategies to keep weeds below the threshold level to ensure the food security of future generations.
- Provides vital information on weed transformation into marketable products using chemical engineering approaches.
- Describes weed management options in organic farming systems.
- Highlights the importance of future scenarios of utilizing weeds as vegetables for human consumption.
- Depicts recent knowledge on integrating traditional and cutting-edge nanoherbicides to manage weeds with an aim to reduce the use of herbicides.

This book would not be possible without the contributions of researchers, farmers, and policymakers committed to advancing sustainable agricultural practices. I extend my gratitude to all who have worked toward effective weed management solutions and to the reviewers and experts who provided valuable feedback during the writing process. Lastly, I would not forget to acknowledge the strategically vital intellectual support offered by my mentors Dr. Asif Iqbal (Associate Professor, Department of Agronomy, University of Agriculture Faisalabad, Pakistan), Dr. Chunjia Li (Sugarcane Research Institute, Yunnan Academy of Agricultural Sciences, China), and Joan G. Lynam (Associate Professor and Program Chair, Department of Chemical Engineering, Louisiana Tech University, Ruston, United States).

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Section 1

Next Generation and Futureproofing Weed Management Strategies

Chapter 1

Introductory Chapter: Future-Ready Nano-Herbicides as a Next-Generation and Futureproofing Weed Management Strategy in Louisiana (Southern United States)

Muhammad Aamir Iqbal

1. Introduction

Among the southeastern states of the United States, Louisiana (LA) state entails diverse ecosystems, attractive cultural heritage, and interesting history. Geographically, LA borders Texas, Arkansas, Mississippi, and the Gulf of Mexico, whereas the Mississippi River serves as a crucial factor in shaping its geographical features, landscapes, diversity of flora and fauna, and economic dynamics. The vital industries in the state include petrochemicals, energy (oil and natural gas), and agriculture, while LA has emerged as one of the nation's leading producers of seafood (particularly shrimp and oysters). Recently, changing climatic scenarios have multiplied the modern challenges in LA, especially environmental degradation. The warm and humid climate of the state favors diversity of plant species including invasive weed (IW) species [1]. Primarily, IW include those plant species that are non-native but spread aggressively in an ecosystem by outcompeting native vegetation leading to serious disruption of ecosystem functioning and services. Interestingly, IW tend to dominate new environments owing to the absence of natural predators causing their unchecked proliferation on a wider scale. These cause a wide array of ecological damages by outcompeting native plant species in terms of growth resources, particularly water, sunlight, and nutrients, by virtue of their superior agro-botanical traits, causing significant reduction in native plants biodiversity and disruption of ecosystem services [2–4]. Most importantly, IW tend to reduce to crop yield and nutritional quality, leading to a serious reduction in the economic turn-out of farmers. This necessitates the application of herbicides which multiply crop's costs of production. Likewise, IW cause soil degradation, while their vigorous growth in water channels alter water flows along with increasing the risk of wildfires in dense vegetation regions [5, 6].

Across southeastern United States, including LA, herbicides (chemical substances encompassing one or more active ingredients, carrier, and sometimes a few impurities) are abundantly applied to keep native and IW species below a threshold level. Broadly, herbicides are classified into selective herbicides (that target specific weeds, such as either broadleaf or narrow-leaf weeds, while crop plants remain unharmed) and non-selective ones (that target all types of vegetation without any discrimination) [7–9]. Likewise, herbicides are further grouped based on mode of action (contact or systemic), application method (pre-emergence or post-emergence herbicides), and their residual effects in the environment (short or long term). Although all types of these herbicides are being applied in LA, however, excessive use has led to environmental concerns as evident in the form of serious soil contamination, pollution in water bodies, and active ingredients retention in crop plants and other farm's produce (fruits, vegetables, fruits, milk, etc.) [2, 10].

This chapter is tailored to underscore the environmental issues emerging from the excessive application of herbicides in southeastern United States. Three vital aspects have been briefly addressed including (i) what sets nano-herbicides apart from traditional herbicides? (ii) what are the defining and core characteristics of nano-herbicides? and (iii) what sort of potential obstacles and technical challenges in the synthesis and application of nano-herbicides on a wide scale can emerge? It has been anticipated that assessing the potential of nano-herbicides for managing native and invasive weed species of LA might be crucial to alleviate the deleterious impacts imparted by the abundant application of traditional herbicides across the United States.

2. Defining and core characteristics of nano-herbicides

Traditional herbicides are available in different formulations such as solution (SL), wettable powders (WP), emulsions (EW), emulsifiable concentrates (EC), suspension concentrates (SC), granules (GR), water dispersible granules (WG), oil-in-water (O/W), microemulsions (ME), microcapsules (CS), and suspo-emulsions (SE). Several distinct and pronounced characteristics define and differentiate NHs from traditional herbicides, whereas the same core features contribute to higher and prolonged effectiveness of active ingredients, precision application to the targeted weed species, and reduced environmental impacts by virtue of higher absorption and reduced release of chemical load into the soil and water bodies. Among these core features, nanoparticle size of active ingredient and carrier substance (1–100 nm) imparts greater penetration into weed tissues (leaves, cuticles, and roots), leading to greater delivery efficiency. The controlled release of active agents present in NHs is one of the defining characteristics that ensures sustained and prolonged effectiveness eliminating the need of repeated applications. Likewise, precision application of NHs can be achieved by making active ingredients responsive to environmental stimuli such as temperature fluctuations, moisture regimes, and alterations in pH. However, such an effort might decrease the stability of NHs owing to degradation by external pedo-climatic factors [11].

Interestingly, higher bioavailability of active agent in NHs may be ensured by virtue of higher solubility into solvents, which is bound to increase the precision of application requiring lesser chemical load and also prevents chemical toxicity to crop plants, unlike traditional herbicides. Another core characteristic of NHs is their potential for uniform dispersion on the surface of targeted weed species, which results in greater absorption and efficacy of active agent. Similarly, one of the strategic traits of NHs may be the preparation of nano-formulations containing the active ingredients, carrier, and other agrochemicals such as plant nutrients. However, research findings are scant on this aspect, and future studies need to focus on this research direction. Last but not least, novel modes of action of NHs are expected to reduce the risk of developing herbicide resistance among native and invasive herbicides by prohibiting them from becoming adaptative to these nano-formulations.

3. What sets nano-herbicides apart from traditional herbicides?

Primarily, nano-herbicides (NHs) are chemical substances that are synthesized using nanotechnology to enhance their potential efficacy, precision, ease of application, and lethal effects in controlling the native and IW species. The NHs-containing nanoparticles are synthesized in nano-formulations aimed at improving the efficiency of the active chemical agents, accuracy of delivery to the targeted weed species, reducing the quantity of active ingredient needed leading to a significant decline in potential negative impacts on crop plants, soil microbiota, water bodies, agricultural workers, food chain, and the environment. In comparison with traditional herbicide formulations, NHs tend to penetrate deep quickly into the tissues of target species by virtue of nano-scale active ingredients. **Figure 1** illustrates a few salient features that set NHs apart from traditional herbicide formulations. Likewise, the controlled release of NHs ensured prolonged effectiveness preventing the need for repeated applications as in the case of conventional herbicides. In addition, improved delivery to the targeted weed species and controlled release of active ingredient are anticipated to reduce the environmental pollution and contamination of soil and water bodies.

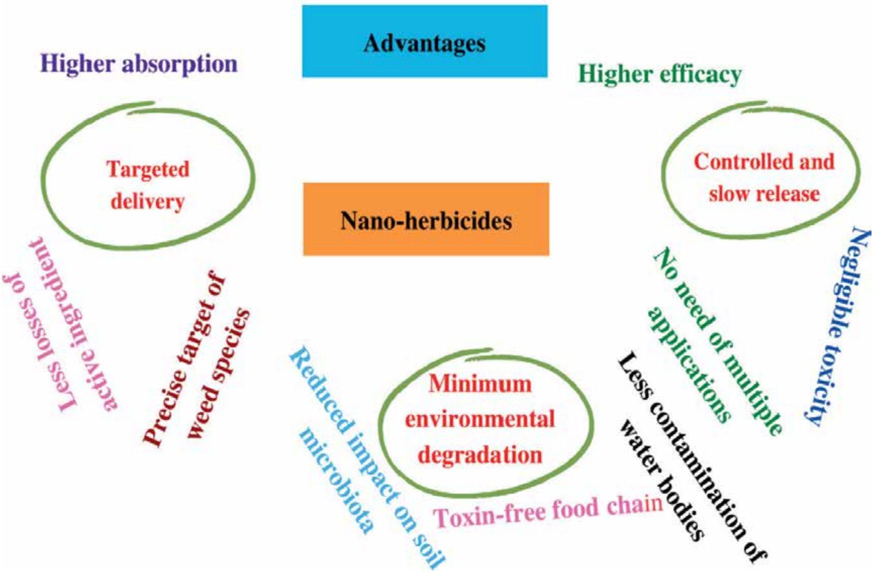

Figure 1.
Pronounced features of nano-herbicides that set them apart from traditional herbicide formulations particularly targeted delivery to weed species, controlled and slow release of active ingredients for prolonged effectiveness, minimum environmental degradation owing to significantly lower release of chemical load into the soil and water bodies, etc.

4. Synthesis of nano-herbicide: Materials and methods

In order to synthesize NHs, different materials are required, such as active herbicidal agents like glyphosate, atrazine, or any other active ingredient which are encapsulated with the nanocarriers such as silica, metal oxides, liposomes, and micelles. Another vital material is required for imparting stability to the NHs, and for this purpose, cetyltrimethylammonium bromide or polyvinyl alcohol can be used

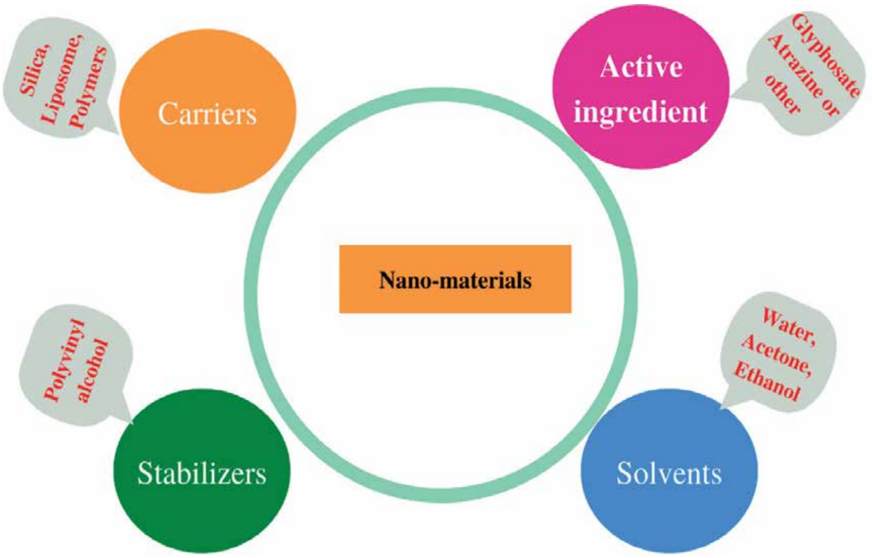

Figure 2.
Materials required to synthesize nano-herbicides such as active ingredient, nanocarriers, stabilizers, and solvents to dissolve nano-formulations before application on the targeted weed species.

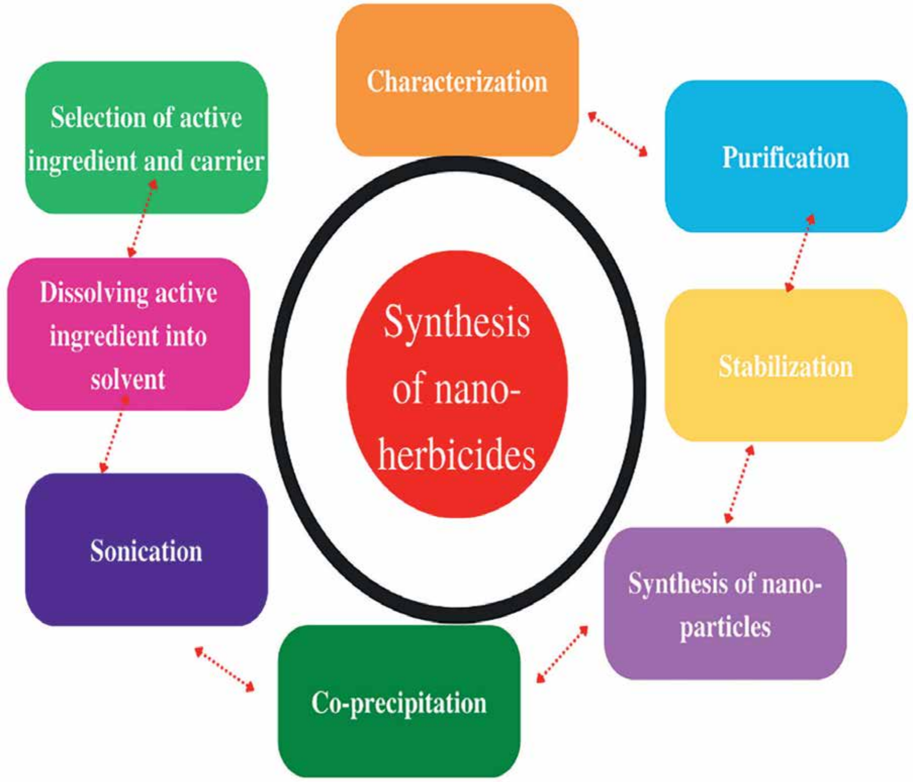

Figure 3.
Protocol to synthesize nano-herbicides entailing steps such as preparation of active ingredient and encapsulation, sonification, and co-precipitation to synthesize nanoparticles.

as a stabilizer agent. In some cases, pH adjusters may also be used depending on the type of active ingredient and nanocarriers. **Figure 2** portrays different materials required for synthesizing the NHs, whereas **Figure 3** presents a protocol to prepare NHs. Selection of compatible active agent and nanocarriers is the first and foremost step (generally referred to as encapsulation), which determines the quality of NHs. Likewise, sonication is performed for thorough mixing of the ingredients. Then, a non-solvent like water is slowly added to precipitate the NHs complex, and nanoparticles are collected by centrifugation or filtration. Subsequently, ultrasonication may be performed to avoid the formation of aggregates and synthesize uniform-sized crystals. Centrifugation can be done for the purification of NHs by removing excessive unreacted ingredients. Characterization is then performed by executing particle size analysis primarily using dynamic light scattering analysis, whereas morphological traits, especially the structure of synthesized nanoparticles, can be observed using a scanning electron microscope or transmission electron microscope. Moreover, UV spectroscopy or HPLC can be performed for assessing the encapsulation efficiency (mixing of active ingredient with carrier), and release profile analysis is used to predict the controlled release of chemical load [10, 11].

5. Potential obstacles and challenges of nano-herbicides and perspective research directions

Although NHs offer numerous advantages over traditional herbicides, however, these also come with potential obstacles and several technical challenges and glitches. One of the prime obstacles in the synthesis of NHs is complex formulation processes requiring sophisticated synthesis techniques such as electrospinning, co-precipitation, and solvent evaporation which constitute key challenges. Additionally, keeping uniformity of particle size of active ingredients in NHs is highly desirable to achieve potential benefits of NHs through consistent release rates and higher absorption by target weed species. Likewise, maintaining the nanoscalability of NHs during production at a commercial scale can be challenging leading to significant inconsistencies in the quality of the final product. Moreover, aggregation of nanoparticles during synthesis, transportation, packing, and storage may cause a significant decline in the stability and effectiveness of active ingredients present in NHs. Similarly, the chemical stability of nano-active ingredients and carriers present in NHs is difficult to maintain over a longer time due to its sensitivity to environmental factors, particularly solar radiation, too high or low-temperature ranges, humidity fluctuations, etc. Furthermore, the shorter shelf life of NHs is a critical factor that is bound to determine the commercial viability of NHs, whereas further research is being carried out to develop protocols for prolonging the storage life of NHs over a longer period of time. Another prime concern has been anticipated in the form of IW tolerance against NHs on the pattern of traditional pattern, and in such a scenario, it may become even more challenging to control those resistant IW across the United States and their invasion of other ecosystems worldwide.

Future research needs to address the low encapsulation efficiency of NHs during the formulation phases, which results in a significant loss of active ingredient, and ultimately, a serious reduction in efficacy takes place. This can be avoided by optimizing the encapsulation protocols, using superior nanocarriers, and ensuring the scaling of active ingredients. Likewise, rigorous studies are needed to study the release kinetics of active ingredients in NHs to ensure a controlled and slow release of the chemical load over time, which requires optimization of release kinetic mechanisms. It is also anticipated that nano-formulations of herbicides may be sensitive and prone to the influence of external stimuli, which require further studies to ascertain the consistency of NHs effectiveness against native and IW species. Likewise, another aspect needs researchers' attention in terms of conducting systematic studies to investigate the interactive impacts of post-emergence NHs (nano-active ingredient and carrier substances) with other agrochemicals, especially foliar-applied fertilizers. Similarly, the use of sophisticated equipment and complex protocols increase the cost of production of NHs, which must be reduced substantially to bring them into the access of farmers. In addition, an effective and universally accepted standard for testing and standardization of NHs must be developed to increase the quality traits, determine the safety levels (agricultural workers through inhalation or ingestion, and skin contact), and boost the acceptance rate of NHs among farming community. Moreover, it is foreseen that nano-formulations of NHs may be lethal to soil microbiota, aquatic life, grazing animals, as well as human beings owing to more penetration capacity by virtue of nanoscaled active ingredients, which require extensive studies before commercialization of NHs across regions. The nano-active ingredients bioaccumulation in food chain also requires serious considerations before wide-scale advocating and adoption of NHs for managing native and IW species [11, 12].

Reliable testing of NHs for safety concerns can increase market acceptance of NHs in the short term. For developing a concise and comprehensive governing policy concerning NHs, regulatory compliance has remained complex, understandably, owing to varying terms and conditions across regions that have hindered the development and commercialization of NHs. Further research on these dynamics and potential challenges may explore more sustainable and effective IW management options by using fewer chemicals and thereby ensuring environmental protection and a toxin-free food chain.

6. Conclusions

Different formulations of traditional herbicides such as solution (SL), wettable powders (WP), emulsions (EW), emulsifiable concentrates (EC), suspension concentrates (SC), granules (GR), water dispersible granules (WG), oil-in-water (O/W), microemulsions (ME), microcapsules (CS), and suspo-emulsions (SE) have been sources of toxicity in food supply chain and environmental pollution. Contrastingly, nano-herbicides contain nanoparticles aimed at improving the efficiency of the active chemical agents, accuracy of delivery to the targeted weed species, reducing the quantity of active ingredient needed leading to a significant decline in potential negative impacts on crop plants, soil microbiota, water bodies, agricultural workers, food chain, and the environment. In comparison with traditional herbicide formulations, nano-herbicides tend to penetrate deep into the tissues of target weed species by virtue of nanoscale active ingredients. However, complex formulation processes in maintaining nanoscalability, uncertain chemical stability, low encapsulation (mixing of active ingredient and nanocarrier) efficiency, and scant studies on the release kinetics of chemical load require more in-depth investigations.

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Chapter 2

Perspective Chapter: From Weeds to Wealth – Hydrothermal Carbonization for Transforming Noxious Broadleaf Weeds of Louisiana into Soil Amendments

Muhammad Aamir Iqbal, Mohammad Tarikuzzaman, Muhammad Saad Atique, Adan Fatima and Joan G. Lynam

Abstract

In southern states of the United States (US), particularly in Louisiana, noxious broadleaf weeds have become undesired flora that tends to dominate crop plants in all types of farming systems. By genotypic superiority-driven robust growth habits and unprecedented reproductive potential, weed species acquire more growth resources (moisture, nutrients, solar radiation, etc.) than crop plants. Weed species can also survive periods of suboptimal growth conditions (salinity, drought, heat, chilling, heavy metal toxicity, water logging, soil erosion, heavy grazing and trampling by livestock, etc.). Considering changing climate scenarios and environmental pollution associated with the extensive use of herbicides, researchers have realized the need to explore and understand the remarkable agro-botanical superiority of weeds. Formulating and re-optimizing weed management approaches has become essential for improving farming practices. To attain these objectives, this study has been tailored to synthesize fundamental knowledge on a few prevalent weeds (e.g., pigweed, alligator weed, Chinese tallow, and parthenium weed) of Louisiana. Moreover, the prevalence of invasive weed species in the region has been objectively analyzed, and an economically viable chemical engineering-based weed management strategy (hydrothermal carbonization) for converting weed biomass into organic soil amendment (hydrochar) has been proposed. Such an approach holds the potential to keep weeds below the threshold level and reduce the use of herbicides, along with imparting sustainability to common Louisiana farming systems.

Keywords: pigweed, exotic weeds, hydrothermal carbonization, hydrochar, herbicide tolerance

1. Introduction

In the United States of America (US), Louisiana is one of the southeastern states, with Mississippi to its east, Texas to the west, the state of Arkansas to the north, and the Gulf of Mexico to the south. The climate of Louisiana is continental subtropical (characterized by hot and humid summers leading to frequent afternoon thundershowers, along with mild winters) owing to its proximity to the Gulf of Mexico. This state lies partway between the Pacific and the Atlantic oceans at the mouth of the Mississippi-Missouri River valley. The fertile soil of Louisiana has provided a rich agricultural legacy since 1860, particularly farming involving the production of diversified crops, including rice, sugarcane, cotton, corn, soybeans, and feed grains, along with sweet potatoes. In Louisiana, modern profit-oriented and input-intensive farming systems are increasingly becoming prone to climate change disruptions (global warming, disruption of rainfall patterns, and frequent incidence of abiotic stresses), anthropogenic disturbances (land use changes), and invasive weed species [1].

Weeds impair a crop's efficiency in utilizing all existing resources for dry matter accumulation and thus affect yield and economic productivity. **Figure 1** illustrates a wide array of interferences caused by weeds that restrict the growth, yield, and quality of crops. Weed infestation causes yield reductions ranging from 35% to total crop failure. That is why selecting the appropriate herbicide is useful in decreasing weed infestations and resistance [2, 3]. Plenty of herbicides are available in the market to prevent weed growth. Herbicides are considered the most effective method to control perennial and annual weeds. However, it is critical to choose the appropriate herbicide and apply it at the right time; otherwise, the crops can be seriously harmed [4–6]. Crop plants and weeds compete for natural and artificial resources such as nutrients, moisture, and field space. Weeds tend to have better survival traits compared to crops (e.g., seed viability, seed dormancy, C4-mechanism, competition ability, prolific seed production, dormancy mechanism, competitive ability, and greater temperature compensation point), and thus have significantly reduced crop productivity and quality

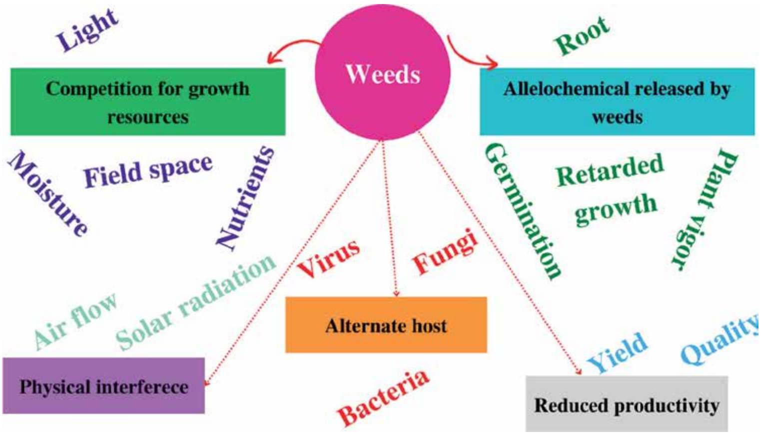

Figure 1.
Different mechanisms of weeds' interference with crop plants, such as allelopathy (causing a reduction in germination, root development, and retarded growth of crop plants), competition for growth resources (moisture, nutrients, light, and space in the field), and physical interference (restricting airflow and solar radiation to crop plants), cause a reduction in productivity in terms of economic yield and nutritional quality of agricultural produce.

throughout the history of agriculture [7, 8]. Weeds cause more economic losses than any other crop pest owing to their superior adaptability to a broader range of environmental extremes, enabling them to thrive and reproduce vigorously in diverse habitats, including degraded and marginal soils [6, 9].

One of the biologically feasible management options could be weed utilization as forage for ruminants, depending on the nutritional profiling of weed species [10]. For this reason, research is needed to determine the nutritional quality traits and presence of toxic compounds in indigenous and invasive weed species abundantly present in crop fields, roadsides, and grasslands [11–13]. Moreover, the identification of weeds producing allelopathic compounds that suppress nearby native plant species is necessary [14–17]. Biological control is an approach to managing invasive weed species like *Parthenium hysterophorus* (parthenium weed) using natural enemies such as insects, pathogens, or other organisms. Furthermore, instead of relying solely on excessive use of herbicides, increased understanding concerning the ecological requirements of noxious weed species may reveal the traits that assist weeds in establishing themselves in new and often unfavorable habitats. However, chemical engineering-based weed management approaches such as hydrothermal carbonization may be useful in converting weed biomass into beneficial and marketable products like carbon-enriched soil amendments.

Therefore, this perspective study has been systematically tailored to deepen the fundamental understanding of the presence and prevalence of the most noxious weeds in the state of Louisiana in the United States. Three pivotal questions have been briefly addressed, including (i) what are prominent noxious weeds and their agro-botanical traits that impart superiority to weeds over crop plants in Louisiana? (ii) what are the chemical control options and the level of herbicide tolerance among these weed species? and (iii) are there any feasible chemical engineering management options like hydrothermal carbonization for converting weed biomass into useful and marketable products?

2. Alligator weed

Alligator weed (*Alternanthera philoxeroides*) is native to South America and has emerged as a noxious aquatic plant in the states of Florida, Mississippi, Alabama, Georgia, and Louisiana in the US [18, 19]. Alligator weed (**Figure 2**) thrives vigorously in hot and humid conditions and can dominate in wetlands, slow-moving rivers, and the standing waters of ponds or lakes. This weed tends to form thick mats on the surface of water owing to dense growth, leading to sunlight blocking and disruption of the aquatic ecosystems. By virtue of its rapid spread and resilience in harsh growth conditions, control options become limited once it gets established. Management strategies for keeping this weed under its threshold level, particularly chemical herbicides, have led to serious ecological damage. Alligator weed tends to dominate native plant species by virtue of its robust growth rate and vigorous vegetative reproduction, as it keeps on producing new plants through the splitting of stems and roots. Due to these unprecedented characteristics, this weed has spread in both aquatic and terrestrial environments across the globe. To make matters worse, alligator weed has better plasticity in withstanding abiotic stresses leading to its spread on marginal and degraded lands as well as in water environments [20].

Several herbicides are being used to target alligator weed, including 2,4-D, diquat, and glyphosate, which often result in harming desirable plants and wildlife along with

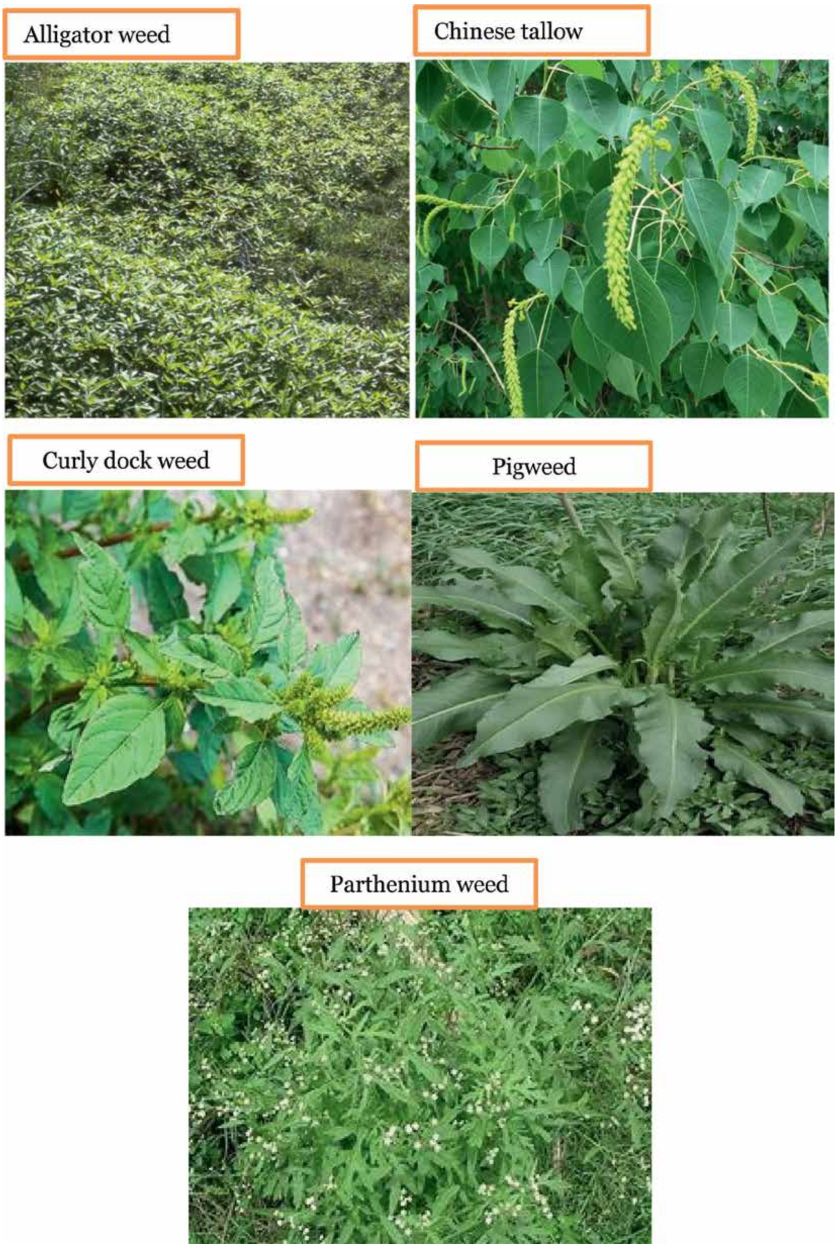

Figure 2.
Five prominent weed species of Ruston, Louisiana (Southern US) for possible conversion into hydrochar by using the hydrothermal carbonization (HTC) technique.

causing environmental degradation due to the long halflife of the active ingredients of these herbicides [21–23]. Recently, research attention has been directed toward the identification and development of biological control options for alligator weed. It has been reported that insects such as alligator weed flea beetle (*Agasicles hygrophila*) feed on alligator weed and significantly reduce the biomass of this weed. However, biocontrol agents have limited efficacy in controlling the weed spread, and it has been advocated to use biocontrol methods in conjunction with other effective management options (e.g., cultural, chemical, and mechanical techniques).

3. Chinese tallow weed

Chinese tallow (*Triadica sebifera*) known by the common name of popcorn tree, has become an invasive weed in many parts of the US (**Figure 2**). It is believed to have originated in East Asia, China, northern Vietnam, and Taiwan. It has successfully naturalized its population in many Asian countries (for example, Japan, Pakistan, Bangladesh, and India), along with Australia and many African and European countries. Recently, it has been identified as one of the problematic weed species in the southeastern US. Chinese tallow has been widely distributed spatially in abundance throughout the Atlantic Coast, particularly in North Carolina and also on the Gulf Coastal Plain. Recently, a significant increase in the population density of Chinese tallow has been reported in Texas, Mississippi, and Louisiana [24]. Mostly, its occurrence in abundance has been associated with low-lying areas, particularly along the waterways, riparian zones, and the Gulf Coastal Plain's prairies [25, 26]. In the Southern US, Chinese tallow has become highly prevalent, with invasion hotspots centered in southeastern Texas and extending into neighboring states, especially Louisiana. Additionally, the Interstate-10 corridor has also been invaded by this weed, and it has extended its presence into the De Soto National Forest and the state of Mississippi. Chinese tallow bears broad leaves, which tend to evolve into heart-shaped leaves that attain bright colors during the fall. It produces small white flower clusters that develop into seed capsules containing seeds having a waxy coating. Birds and other animals often disperse the seeds [27, 28]. The waxy coating of the seeds enables them to float on water, aiding their dispersal to far-flung areas. Chinese tallow has been subjected to systemic herbicides (glyphosate, triclopyr, etc.). The efficacy of these herbicides was multiplied when cut stumps or foliage of Chinese tallow came into direct contact with systemic herbicides. As of now, scant research strides have been made specifically for Chinese tallow to keep it below the threshold level through biological control options. However, future research might identify potential biological agents for the effective management of this noxious weed across the Southern US.

4. Pigweed

Pigweed is a common name for different weed species, primarily belonging to the Amaranthaceae family. The most noxious species is called palmer amaranth (*Amaranthus palmeri*) (**Figure 2**), which, by virtue of its robust vegetative growth and herbicide tolerance, has posed a serious challenge to modern farming systems [29]. Redroot pigweed (*Amaranthus retroflexus*) is another noxious species generally identified by broad leaves and dark reddish stems. Primarily, it thrives well on disturbed soils. However, it tends to pose a significant competition to crop plants. Additionally, smooth pigweed (*Amaranthus hybridus*) attains the appearance of redroot pigweed at vegetative growth stages, while it may be distinguished by its smoother leaves and presence of fewer hairs in comparison to redroot pigweed. Although pigweed species have become troublesome owing to aggressive growth habits and tolerance against most of the herbicides, these species have also been found to be nutritious and have the potential to be utilized in traditional food recipes [30, 31]. Different pigweed species (Palmer amaranth, redroot pigweed, and tall waterhemp) adversely impact soybean, corn, and cotton crops in the southeastern US [30, 32, 33]. Additionally, pigweed species tend to dominate vegetable gardens and rights-of-way by dominating the grass species. The higher survival rate of pigweed under abiotic stresses and environmental extremes is due to its huge production of seeds. Chemical control of pigweed species has remained the most dominant strategy; however, increasing tolerance has been reported particularly against herbicides involving protoporphyrinogen oxidase inhibitors, synthase inhibitors, photosystem II inhibitors, synthetic auxin herbicides, 5-enolpyruvylshikimate 3-phosphate synthase inhibitor, 4-hydroxyphenylpyruvate dioxygenase inhibitors, and microtubule inhibitors [30, 32].

There are limited pre-emergence herbicides somewhat suitable for controlling pigweed species such as atrazine (works well in crops like corn), S-metolachlor (suitable for application in many cereal and leguminous crops), and pendimethalin (preferably applied in soybeans). Among post-emergence herbicides, paraquat, 2,4-D, glyphosate, and dicamba are a few of the instances that are being applied extensively to keep pigweed species below threshold levels. However, herbicide tolerance in pigweed against these broad-spectrum herbicides has been increasing over time, further limiting the management options.

5. Sour dock (*Rumex dentatus*) and curly dock (*Rumex crispus*)

Sour dock belongs to the Polygonaceae family and has persistently remained a noxious weed in planted fields. This annual weed is believed to have originated in southern and eastern Asia. It tends to establish itself in varying agroclimatic and soil conditions and holds potential to prevail in neglected areas, particularly along water channels and riverbanks. The Polygonaceae weed, *R. dentatus* generally grows and prevails in fields having wheat, potato, and mustard (**Figure 2**). In addition, this weed suppresses the growth of crop plants by releasing allelochemicals through its roots. In a few regions, it is being consumed as a leafy vegetable, which assists in keeping its population below the threshold level in a biologically viable manner [34].

Among the broadleaf weeds, sour dock has emerged as one of the prime concerns in irrigated crops, particularly wheat in rice-wheat cropping systems, globally. This weed tends to dominate the wheat fields due to its high seed production potential and its ability to survive suboptimal growth conditions. In addition, its highly competitive growth traits (both below and above ground) enable it to quickly reproduce and ultimately cause drastic yield reduction due to heavy infestation. Depending upon the level and time of infestation, crop stage, soil fertility status, and agroclimatic conditions, yield losses in wheat could be up to 67% [35].

Recently, owing to continuous use of metsulfuron-methyl (acetolactate synthase-ALS enzyme inhibitor weedicide), *R. dentatus* has evolved resistance against it along with other popular herbicides such as pyroxsulam, iodosulfuron, florasulam, and triasulfuron. To control and keep herbicide-resistant weeds below threshold levels, integration of cultural, mechanical, chemical, and biological weed management strategies is required. Particularly, the use of herbicides with alternate action modes needs future studies. Furthermore, farmers must practice preventive strategies, especially using weed-free certified seeds for crops, systematic and regular field scouting, sanitization of farm equipment to restrict weeds' seed movement across fields and regions, along with manual removal and disposal of weeds iflow-cost labor is available. The use of *Alternaria alternata* (a fungal pathogen) caused severe necrotic spots on the leaves of *R. dentatus*. A mortality rate of over 70% was caused by *A. alternata* pathogen [34]. Recently, it has been reported that *Galerucella placida* Baly (Coleoptera: Chrysomelidae) larvae and adults tend to consume this weed. Therefore, it is proposed to investigate viable herbicides containing volatile organic compounds (VOCs) for controlling this weed directly and through attracting biocontrol agents like *G. placida* on a sustainable basis.

6. Parthenium weed

Parthenium hysterophorus L. (Asteraceae), also known as star weed and congress weed (**Figure 2**), has become one of the most noxious broadleaf weeds of global concern owing to its presence and prevalence in over 50 Asian, European, and North American countries [36]. It is an annual herbaceous plant having deeply lobed and serrated leaves resembling ragweed leaves. Its flowers are small and white and are produced in clusters, while its stems can attain a height of over 1–2 meters. The prolific seed production potential of Parthenium has been attributed to its invasive nature. It is known to cause numerous health challenges for humans, particularly skin irritation (dermatitis) and respiratory problems in individuals suffering from different types of allergies. Livestock that consume parthenium-contaminated forage may experience toxicity and health complications. Parthenium is believed to have originated somewhere in Mexico and Central America and has rigorously expanded its geographic range during the last decade. Currently, this weed is feared to invade much larger swathes of agricultural land, grasslands, water channel bunds, and roadsides in the near future [37]. It has been known to significantly reduce local flora biodiversity and productivity efficiency of farmlands, along with imparting deleterious effects on animals and human health [38].

Interestingly, this weed has become prevalent in all countries of South Asia (particularly India, Pakistan, and Bangladesh) and is rapidly spreading in European and African countries due to its vigorous growth habits, superior agro-morphological traits, and unmatched reproduction potential [38]. Its suitability and potential to survive a wide range of climatic variations and its invasion of cotton (*Gossypium hirsutum* L.) growing areas of the US may pose a serious threat to the cotton industry. Besides competing for growth resources with crop plants, it serves as a secondary host of numerous crop diseases (tobacco streak virus) as well as insects including cotton mealybug (*Phenacoccus solenopsis* Tinsley). Recently, modeling approaches have suggested that Parthenium weed is likely to spread vigorously in the regions that are irrigated with the Indus basin irrigation systems of Pakistan. Currently, biocontrol of Parthenium has been suggested by using a beetle called *Zygogramma bicolorata*. For the growth of this beetle, the northern districts in the province of Punjab (Pakistan) have been regarded as the most suitable regions. However, the southern Punjab districts, the northern parts of Khyber Pakhtunkhwa province, and the whole of Sindh province seem to be unsuitable for its growth. The global warming induced by climate change has restricted *Z. bicolorata* growth in regions within the Punjab province. Moreover, the climate of Pakistan's administered Azad Jammu and Kashmir (AJK) region also has the potential to promote the growth of this beetle for controlling Parthenium weed. Interestingly, the biological control agent (*Z. bicolorata*) has been predicted to benefit from the temperate conditions of AJK. Thus, to restrict further invasion of Parthenium in new areas, there are opportunities to utilize biocontrol approaches using *Z. bicolorata* to keep this noxious weed under control.

Among herbicides, glyphosate is a nonselective herbicide that inhibits specific enzyme pathways, which leads to suppressed growth of weeds, and can be effectively utilized against Parthenium, preferably at pre-flowering stage. Among systemic herbicides, imazapyr holds potential to adversely affect the growing tissues of parthenium by inhibiting enzymes involved in the synthesis of branched-chain amino acids leading to the death of plants. Being a nonselective herbicide in action, its use might be preferably recommended for use in non-crop areas to control parthenium. Likewise, paraquat is another nonselective herbicide that restricts weed's growth by producing within plant cells highly reactive oxygen molecules, causing cell damage and eventual death. Although it acts fast, careful consideration must be given to avoid damage to nontarget crop plants. Additionally, dicamba, also a nonselective herbicide, disrupts weed growth by mimicking auxin. However, it effectively leads to the suppression of weed growth. It might be used in combination with glyphosate and metsulfuron-methyl to enhance its efficiency in controlling parthenium weed. Moreover, 2,4-D, a selective herbicide, might be utilized in combination with other herbicides to control broadleaf weeds like parthenium. The underlying mechanism of this herbicide is its capability to mimic the plant hormone called auxin that triggers uncontrolled growth, leading to the wilting of weeds.

7. Chemical engineering management options: Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a technique that combines dehydration and decarboxylation processes for a biomass sample to elevate its carbon content for achieving a higher calorific value. It encompasses a process aimed at converting biomass or organic materials like weeds into carbon-rich solids (commonly referred to as hydrochar) by employing heat and pressure in the presence of water [39]. Primarily, the HTC process intends to simulate the formation of natural coal from biomass, and this conversion generally takes place on a much shorter timescale. The HTC process entails many different steps, as the feedstock preparation constitutes the basic step. In this step, organic wastes (crop residues, food waste, municipal solid waste, etc.) are typically shredded and uniformly ground to ensure uniformity of feedstock samples. The following step is to execute the hydrothermal reaction in a high-pressure reactor involving biomass feedstock mixing with water under increasing heat regimes. In the high-pressure reactor, the temperature is generally kept at 180–250 °C, whereas pressure is also maintained to retain water in a liquid state [40, 41]. Afterward, there comes the most pivotal step of carbonization, encompassing the chemical reactions leading to hydrochar formation and aqueous byproducts. Generally, the chemical reaction of biomass conversion under high temperature and pressure is facilitated by deionized (DI) water to assist in the breakdown of complex organic molecules present in the biomass samples. Finally, product separation (hydrochar is separated from liquid byproducts) is performed once the chemical reaction is complete. The liquid portion of HTC products contains several dissolved organic compounds that can be further treated or reused, whereas solid hydrochar can also be used directly as an organic soil amendment or processed further.

8. Advantages and limitations of HTC for weed biomass conversion

HTC is a simple process in which weed biomass can be submerged in water and thereafter heated at elevated temperatures (180–350 °C) for 5 minutes to 4 hours by maintaining pressure to keep water in the liquid state [42, 43]. This technique offers advantages by employing diversified chemical reactions, including dehydration, decarboxylation, pyrolysis, aromatization, and polymerization, with an aim to reduce the content of hydrogen and oxygen in the biomass. These processes cause loosening of the components that tend to bind the lignocellulosic structure, and ultimately, cellulose and hemicellulose are released. Furthermore, cellulose is hydrolyzed in HTC reactions resulting in glucose, and hemicellulose is hydrolyzed to various hexoses and pentoses [41].

One of the prime advantages of weed biomass conversion using the HTC process is the production of an organic soil amendment called hydrochar. By virtue of abundant organic carbon content, hydrochar holds the potential to improve soil organic matter, structure, microbial activities, and overall soil fertility and health. The HTC process involves temperatures and pressures that would inactivate any seeds remaining in weeds, unlike typical composting processes that may be an alternative for weed use. More importantly, this chemical process becomes even more important because of carbon sequestration, which can go a long way in reducing farming-related greenhouse gas emissions Besides weed biomass, crop leftovers and wastes can also be converted into organic soil conditioners (hydrochar) leading to the prevention of the open-field burning practice for unwanted biomass. Hydrochar can also be used as a solid fuel, offering a potential renewable energy source for farm activities. Moreover, weed biomass conversion into hydrochar and other products holds the potential of reducing the use of chemical herbicides, leading to reduced ecological degradation, soil and water contamination, and environmental pollution. Other applications of HTC processing could include municipal waste treatment for conversion into organic manures to be applied in conjunction with weed-derived soil conditioners.

Concerning a wide array of challenges for the conversion of weed biomass into organic amendments, future research needs to focus on determining the economic viability of the HTC process. This can be performed by estimating fixed and variable costs pertaining to the weed biomass collection, drying, and sample preparation, along with energy requirements for carrying out the HTC process. On the other hand, the price tag of carbon-enriched organic amendment might be adjusted as per cost of production, market demand, and other localized factors. In addition, process optimization concerning the pressure, temperature, and reaction time for weed biomass conversion into hydrochar remains an aspect requiring in-depth research because achieving optimal quantities of carbon-enriched hydrochar requires optimal conditions during the HTC process. To sum up, hydrothermal carbonization holds the potential to offer a biologically promising technology to convert weed biomass into valuable organic soil conditioner. Moreover, reduced application of herbicides by utilizing weeds in HTC might address environmental concerns (due to retention of herbicide's active ingredients in plants, water, and soil) and waste management-related challenges.

9. Conclusion

In southern states of the US, particularly in Louisiana, weeds have posed a serious challenge to modern intensive farming systems by reducing crop yield, nutritional quality, and economic outcomes by increasing the cost of production. In addition, excessive use of herbicides has gradually imparted tolerance in noxious weed species against most of the broad-spectrum herbicides, thus limiting the available choice of active ingredients. Therefore, future studies need to address invasive weed species' challenges, especially their prevalence in agricultural farmlands. In addition, future research needs to study the interplay of different anthropogenic-climatic drivers that promote weed invasion and establishment in far-flung agricultural lands. Likewise, weed management options need to be devised that consider their merits and trade-offs to discover possible synergies among management options. Moreover, interdisciplinary and cross-disciplinary research must target integrating agronomic, botanical, and chemical engineering-based management options like hydrothermal carbonization to convert weed biomass into organic amendments for degraded and marginal soils. Furthermore, it is high time to sort out technical challenges for optimizing hydrothermal carbonization to attain maximum quantity and high-quality products like hydrochar on a sustainable basis. Such an approach holds the potential to reduce the application of herbicides along with offering environmental protection, ecological restoration, and human health benefits (due to lesser retention of chemical ingredients in agricultural produce) and bolstering the economic profitability (through reduced production of cost and improved value and sale price for the produce) for farming communities.

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Chapter 3

Perspective Chapter: Management of Weeds in Organic Farming System – Special Focus on Organic Vegetable Farms of the USA

Swati Shrestha, Karina Beneton, Ma. Gweneth Abit,
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Abstract

Weed management is an important challenge in all farming systems, but it is more complicated in organic farming due to lack of chemical options. Concern about potential increases in weed populations without the use of herbicides has limited the uptake of organic farming even though organic products are gaining popularity among consumers. Different weed management strategies differ in their ability to control weeds, and often have unique agroecological implications. Broadleaf weeds, grasses and sedges are the three major classes of weeds impacting quality and yield in both horticultural and row crop systems. In an organic production system, the major concern is how and when to adopt the management practices to make the system productive and profitable. Generally, an integrated management approach using organic herbicides, mechanical, cultural, and biological practices is considered best for weed control in organic system. However, a systematic literature on different methods for weed management in organic farming system is not well developed. This book chapter outlines major weed problems in organic farming and various methods of weed control. The chapter is expected to disseminate information on strategies for sustainable weed management in organic farming systems.

Keywords: weed management, ecological, integrated, organic farming, sustainable

1. Introduction

Organic farming is an agricultural system that operates on the principle of utilizing internal resources within the farm system and resorting to external inputs only when necessary. By incorporating modern technology selectively and avoiding environmentally risky elements, the practice aims to maintain harmony between farming practices and the natural environment [1]. Through techniques such as increased organic matter content, crop rotations, and conservation systems, organic farming fosters soil health, minimizes compaction, and mitigates erosion without the environmental hazards associated with excessive herbicide use in conventional methods [2]. In the global market year 2021, the world organic foods market size was valued at 140.46 billion dollars [3]. In the USA, organic food market size was estimated to be worth over $52 billion in 2020 and is projected to have a 10% growth during the forecast period 2023–2028 with increasing demand from consumers [3]. Organic farming in the United States was initiated approximately three decades ago after the establishment of the 1990 Organic Foods Production Act that contributed to increase in certified organic agricultural production areas in the country [4]. The organic industry in the United States is one of the fastest-expanding agricultural areas [5]. Consumer demand for organic products is a primary driver of organic vegetable production. Many people choose organic vegetables because they believe these are healthier and contain less pesticides than conventionally grown vegetables [6]. As a result, farmers and producers respond to these demands by increasing organic vegetable cultivation.

Common organically grown vegetables in the United States includes fresh tomatoes, onions, and squash with largest number of organic operations in the USA totaling 1847, 1487, and 1347 farms, respectively in the year 2014 [7]. **Table 1** lists top five organic vegetables grown in the USA and their major weeds and **Table 2** lists most common and most troublesome weeds in the organic system within the United States [8].

For many organic growers weed management remains one of the most resource-intensive management activities from the perspective of time, effort, input costs, potential impact on crop yield and quality, capital investment, and energy consumption. There are few times of the year when a grower is not actively working on some aspect of weed management [9]. Numerous grower surveys of organic agriculture demonstrate that weed control remains a major and enduring challenge [10–13]. Because of that, the growers need to combine the crop, soil type, and weeds to be controlled and which method will be most efficient for them.

Typically, weeds are the major limitations to yield in organic farming system. Conversion from conventional farming practices to organic production results in lower yield with an estimate of about 20% lesser yield during the first years but improves over time through better soil fertility and weed management strategies

Vegetable crop		**Primary weeds**	
Common name	**Scientific name**	**Common name**	**Scientific name (Respectively)**
Tomatoes	*Solanum lycopersicum* L.	Dodder, field bindweed, nightshade, yellow nutsedge	*Cuscuta campestris*, *Convolvulus arvensis* L., *Solanum nigrum*, *Cyperus esculentus*
Onions	*Allium cepa*	Lady's thumb, common purslane, red root pigweed	*Persicaria maculosa*, *Portulaca oleracea*, *Amaranthus retroflexus*
Squash	*Cucurbita* spp	Bindweed and perennial weeds	*Convolvulus arvensis* L
Spinach	*Spinacia oleracea*	Common purslane, Common nettle, goosefoot, Shepherd's purse	*Portulaca oleracea, Urtica dioica, Chenopodium album, Capsella bursa-pastoris*
Sweetcorn	*Zea mays*	Nightshade, chickweed, common Lambsquarters	*Solanum nigrum, Stellaria media, Chenopodium album*
Potatoes	*Solanum tuberosum*	Sandburs and foxtails	*Cenchrus* spp. and *Setaria* spp.

Sources: Economic Research Service, USDA 2016 [6].

Table 1.
List of common organically grown vegetables in the U.S. and their primary weeds.

United States Weeds	
Most common	**Most troublesome**
Pigweed spp. (Genus: *Amaranthus* spp)	Pigweed spp. (Genus: *Amaranthus* spp)
Common lambsquarters (*Chenopodium album*)	Nutsedge spp. (Genus: *Cyperus*)
Nutsedge spp. (Genus: *Cyperus* spp)	Common lambsquarters (*Chenopodium album*)
Large Crabgrass (*Digitaria sanguinalis*)	Morningglory (Genus: *Ipomoea*)

Pigweed spp. Included Palmer amaranth, tall water hemp, prostrate and tumble pigweed.
Nutsedge spp. Included annual sedge, purple and yellow nutsedge.
Morningglory spp. Included tall, ivyleaf and pitted morningglory.
Crabgrass spp. Included large, smooth, and southern crabgrass.

Table 2.
Major weeds of organic vegetable production system in the U.S [6].

adoption [14]. However, yield loss in organic production is also correlated with pests and diseases contributing to organic-conventional yield gap.

There are only a few approved crop protection products for organic production system that limit the control of weeds, pests, and diseases organically [15]. Moreover, studies are showing that adaptation of organic agriculture performs best under integrated pest management conditions and might close or reduce the yield gap between organic and conventional systems [16, 17]. For instance, in certain cases, organically managed areas gave higher yields compared to conventional systems under conditions like prolonged periods of low rainfall due to better water-holding capacity of organically farmed soils. Over the years, improvement of management strategies and crop varieties may close the yield gap of organic-conventional farming [18].

In organic farming, a variety of strategies are employed for effective weed management. Common tillage practices, such as hand weeding, hoeing, and the use of mechanized equipment like cultivators and rototillers, are widely utilized [19]. However, the success of tillage depends on the timing and frequency of operations, and prolonged, continuous tillage may have adverse effects on soil quality [20].

Another weed management approach involves the use of dead organic mulches, derived from natural materials and waste by-products. These mulches, compose of materials like straw or wood chips, gradually break down, enriching the soil with organic matter and fostering beneficial microorganisms. Acting as a protective layer, they mitigate erosion, control weeds, regulate soil temperature, and conserve moisture, promoting sustainable and ecologically sound soil management [21].

Cover crops and living mulches, comprising grasses, legumes, or other broadleaf plants, play a pivotal role in organic farming by enhancing soil organic matter, suppressing diseases and weeds, and providing habitat for beneficial insects [22]. However, careful selection is paramount to prevent competition with the main crop and the potential proliferation of pests. Strategic choices, tailored to the specific needs of the farming system optimize the positive impacts of these practices, contributing to improved soil health and overall sustainability.

Crop rotation, involving the systematic planting of different crops on the same land each season, is crucial in organic farming. It helps prevent soil diseases, controls insect pests and weeds, and fosters soil health [23]. Diversifying crops applies varied selection pressure on weeds, preventing the dominance of any species.

An innovative method for controlling weeds in organic farms involves allelopathy. In this approach, crops release allelochemicals to hinder the growth of nearby plants/weeds [24]. Suppression of neighboring plants occur through root exudation, leaching from plant tissues, and volatilization from aboveground parts. Factors such as soil hyphae and arbuscular mycorrhizal fungi enhance the movement of allelochemicals, making this method effective in weed control without harming the environment or increasing management costs [25].

For comprehensive and sustainable weed control in organic vegetable production growers can adopt a combination of these practices described above, falling under the concept of integrated weed management. However, the management decision adopted by an organic grower depends a lot on economic goal of the grower. In many cases, significant price premiums can substantially enhance gross returns in organic farms even when the crop yield is lower than conventional farms. The price difference in return per unit product between the organic and conventional farms influence the economic threshold or break-even points for weed control in organic farms. Consequently, organic growers are economically motivated to tolerate higher weed populations in their fields [26]. This chapter aims to review different organic weed control methods for a better understanding of weed control strategies and developing a good decision-making practice for improved organic vegetable production.

2. Methodology

In the current study, data were collected from secondary sources through bibliographic search and based on the keywords of interest to the authors in google scholar to perform an integrative review. Bibliographical survey is one of the best ways to initiate a study and search for similarities and differences among the articles of interest. The electronic compilation of information is a major advance for researchers as it democratizes access and provides frequent update [27]. The authors finalized different sections of the chapter by topics and worked on their assigned sections before the chapter compilation. During the search some keywords used were weed control, weed management, organic farming systems, non-chemical weed management, and integrated weed management.

3. Ecological approach to weed control in organic system

Organic agriculture is believed to have several health and environmental values such as higher biodiversity, improved soil and water quality per unit area, enhanced profitability, and higher food nutritional value [28]. However, this production system requires intensive management in terms of nutrients, especially nitrogen, and weed management [29, 30]. Nitrogen in natural soil is limited and the supply is dependent on cover crops, organic fertilizers, composts, and soil organic matter [29]. The supply of nitrogen and the control of perennial weeds are classified as the two most important yield-limiting factors in organic production [31]. With sufficient available nitrogen, plants can have competitive advantage as they would have faster growth greatly suppressing weed development [32]. Thus, apart from weed management efficient and effective supply of plant nutrients, especially nitrogen, should also be one of the major priorities of organic growers.

Weed management is a great challenge in organic production system because it eliminates the option of synthetic pesticides. Thus, high manual weeding is one of the widely used option for organic vegetable farming such as sweet corn, spinach, beets, onion, and carrots [33]. Weed control is considered one of the significant problems in organic farming and their effective management is imperative to avoid yield losses and ensure food security.

In the United States, most of the organic production is concentrated in the Western U.S. especially in California [34]. In California, the growers have adopted large-scale conventional farming and used a "zero seed rain" approach for weed control [33, 34]. The zero seed rain system ensures that weeds are controlled before flowering so reproduction and dispersal of weed seed from the parent plant is mitigated [35]. In one of the organic weed management studies, for the "zero seed rain" system, beds and paths were scouted, and appropriate control measures were followed every 2 weeks throughout the growing period with the goal of avoiding weed seed inputs to the seedbank [36]. The hierarchy of weed management tools starts with managing weed seed rain and the seedbank, Merfield in 2023, explained that weed seed rain" is when weeds set viable seed that replenishes the weed seedbank [37]. The importance of minimizing the weed seed rain, and therefore minimizing the size of the weed seedbank. The researchers claimed that using the zero seed rain approach reduced their weed seedbanks and ultimately minimized the weed management strategies in long run [36, 37].

In the organic farming system, both small and large-scale vegetable farmers have the same goal of investing less time and resources for managing the weed population. In response to this goal, growers should aim to control weed seedlings before they reach reproductive/seeding stage, while other focus should be on depleting the number of weed seeds in the soil [38]. In general, weed seeds are controlled during "critical period of weed control". The critical period refers to the stage of the crop growth cycle in which weed infestation must be controlled to avoid significant yield losses [39]. However, there will be an increase in weed seedbanks and an increase in weed emergence in subsequent crops if weeds are only controlled during the critical period [36, 37]. If weeds are only controlled in this critical period, later-emerging weeds may proliferate leading to increase in weed seed bank over a period [31, 40]. Thus, for sustainable weed control in organic system, regular scouting, and appropriate control whenever necessary should be considered by the growers.

4. Current status of organic farms in the United States

The growth of the organic market and consumers demand has led to the adoption of organic farming by more growers in recent years. Most of the organic growers use combination of physical, cultural, biological practices for weed control. In a nutshell, integrated approaches include those that prevent, avoid, monitor and/or suppress all types of pests, plant diseases, weeds, nematodes [41, 42]. However, it is more difficult to estimate Integrated Pest Management adoption rates, given that there is no single, ongoing program or standardized approach, but rather periodic and often disparate assessments [43]. According to the USDA NASS [44], there are 48 certified organic farms in Oklahoma, this is a small number when compared to total farms in the US 17,445 or when compared to top 5 producing states that are led by California with 3061 farms, New York (1407 farms), Montana (206 farms), Wisconsin (1455 farms), and Texas (258 farms) (**Figure 1**). There has been a 5% increase in the number of organic farms in the U.S., from 2019 to 2022 [44].

The top three states with the most area under organic production system includes California, followed by New York and Montana (**Table 3**). Likewise, the top three organic products in the USA are milk, broiler chickens and eggs, followed by apples,

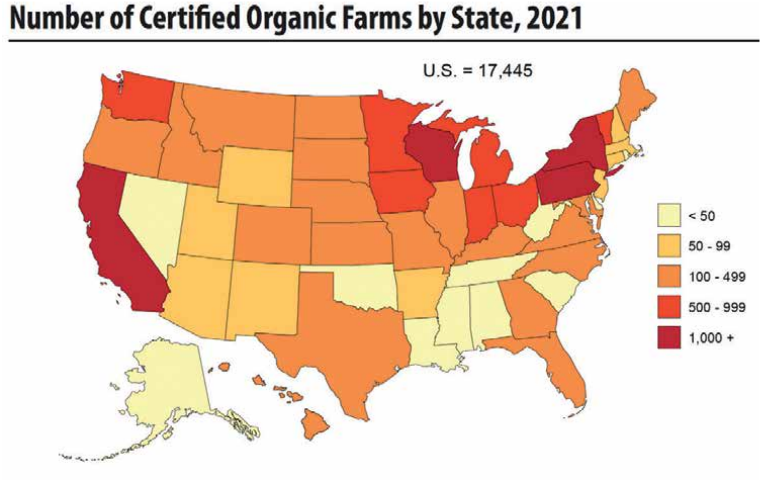

Figure 1.
Number of certified organic farms in the USA. Adapted from Certified Organic Survey, NASS/USDA 2022 [33].

Top states: Certified organic acres	
State	**Thousand acres**
California	814
New York	331
Montana	320
Wisconsin	245
Texas	241
Oregon	228
Idaho	216
Vermont	203
Colorado	191
Iowa	169

Adapted from NASS/USDA 2022 [33].

Table 3.
States with highest number of certified organic farms in the USA.

grains (for corn) and then the fruits and vegetables, as shown in **Tables 4** and **5** respectively.

Demand for organic produce and meat has been on the rise in the USA. For instance, from 2016 through 2019 organic product sales doubled in the state of Oklahoma [44]. The latest USDA data on organic crops show continued growth in the number of certified organic farms and acres nationwide [44]. Even though, some of the U.S. states have adopted organic farming more openly, some other states have lower number of organic farms. For example, Oklahoma has about 3.8% of both the farms and the agricultural land in the U.S., and nearly 2% of the agricultural sales. In the organic sector, though, Oklahoma has just 0.2% of the farms, and less than 0.02% of the sales, nationwide (**Figure 2**).

Commodity	$ million
Milk	1633
Broiler Chicken	1509
Eggs	1221
Apple	629
Corn for grain	424
Strawberries	336
Cattle	316
Grapes	309
Lettuce	276
Soybean	242

Adapted from NASS/USDA 2022 [33].

Table 4.
Major organic commodities in united states, dollar value.

Vegetable	Harvested	
	Farms	Acres
Tomato	10	8
Broccoli	4	2
Green Onion	5	2
Lettuce	7	5
Onion	5	1
Potato	7	4
Squash	5	5
Sweet Potato	4	142
Other Vegetables	10	28

Adapted from NASS/USDA 2022 [33].

Table 5.
Major organic commodities in united states, production acreage.

5. Major weeds in organic vegetable production and their management

In vegetable cropping systems according to Baker and Mohler, 2015, organic vegetable farmers considered common purslane (*Portulaca oleracea*), common chickweed (*Stellaria media*), and hairy galinsoga (*Galinsoga quadriradiata*) as weed species that are most problematic for production [45]. In a survey by Jabbour et al. 2014, 23 organic farmers were interviewed in New England (19 of whom grew primarily vegetables), and they reported crabgrass (*Digitaria* spp.) and *G. quadriradiata* as their most problematic weed species. In that analysis of seedbanks, *Digitaria* spp. and *G. quadriradiata* were more abundant (mean 2456 and 840 seeds m^{-2}, respectively) than *P. oleracea* and *S. media* (mean 284 and 239 seeds m^{-2}, respectively) [38]. All these species tend to set seed rapidly after emerging.

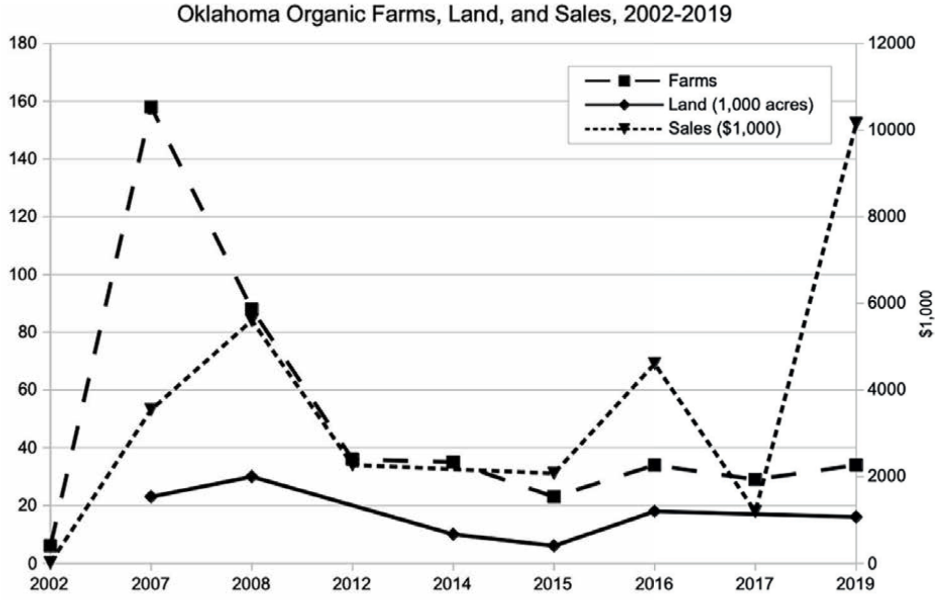

Figure 2.
Organic farms in Oklahoma, Source: NASS/ USDA 2022, Organic Survey.

For example, *G. quadriradiata* can produce viable seeds within 35 to 40 days of plant emergence [46, 47].

Organic crop production has different ways of controlling weeds and some of them are discussed herewith. Crop rotation is among the most popular cultural practices for weed suppression in organic farms. This cultural technique reduces weed survival in the soil seed bank, suppresses weed seedling emergence, and minimizes seed production of weeds that escape the control method [48]. Effective crop rotations are the foundation of cropping systems [49]. Rotations are designed to contain crops with varying life cycles. Weeds that are common during the cool season, such as downy brome (*Bromus tectorum*), are easily handled throughout the growing season of warm season crops, eliminating downy brome seed production in the first cropping [48]. Crop selection for an organic grower is complicated by the requirement to consider soil fertility levels within the cropping sequence and to incorporate fertility-building times in the rotation. Variations in crop and weed responses to soil nutrient levels can also play an important part in weed management [30]. In vegetable production, it was traditionally recommended to include potato (*Solanum tuberosum*) in the rotation of crops to reduce weed problems before a less competitive crop was grown [10]. Vegetables having weak competitive abilities are onions (*Allium cepa*), carrots (*Daucus carota*), and leeks (*Allium porrum*) [50].

Another way of controlling weed density is through cover crops. The inclusion of cover crops in the cropping system helps produce an environmentally friendly vegetable production by providing agroecological services in the field like maintaining soil fertility and preventing soil erosion [30]. The most common cover crops used in organic production are legume crops that contribute to soil fertility through nitrogen fixation. Casini and Olivero reported that the allelopathic effect of cover crops like jackbean (*Canavalia ensiformis*) and velvetbean (*Mucuna pruriens* var. *utilis*) can suppress the growth of cogon grass (*Imperata brasilinsis*) [51]. Moreover, Grundy et al.

noted that allelopathic ability may also play a role in reducing weed development, but it is the weed suppression caused by competition for growth factors that is the main effect of a cover crop [52].

Biological control is a form of "ecologically based pest management that uses some kind of organism (the natural enemies, for example: nematodes, plant pathogens, fishes, goats) to control pest species [53]. This kind of control in organic farm can be naturally occurring, or foreign agents classically introduced and established for ecosystem benefits. Other biological control options used in organic farms include pheromones used for monitoring pest populations and to disrupt mating, sterile insect releases, biopesticides which are pesticide formulations made from living organisms or the products of living organisms [54]. Additionally, bio stimulants which are biological products can also reduce the impact of pest activity because of a complex constituents or indirect mode of action that improves plant tolerance to abiotic stresses, and not because of the sole presence of a known plant protective compound acting directly on pests [55–57].

In summary, Integrated Pest Management helps the farmers in several ways to control, manage and avoid the multiplication of weed seeds. Even with IWM resulting in excellent results, it is necessary to define a hierarchy in this management to develop the best possible way in a most economical way.

To achieve the best weed management for the least cost, the focus of weed management must be on the components in the top half of the table (**Table 6**). The first five are considered to achieve most of the weed management, especially in vegetables systems. The crop rotation is the most effective means yet devised for keeping land free of weeds. No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping [58]. Another alternative to control weeds in a sustainable agricultural system is using synthetic materials or plant residues/waste on the soil, also known as mulching [59]. Mulch film improves soil temperature and moisture, providing a suitable environment for enzymes produced by the microorganism community and improving soil productivity. The additional advantage of mulching is improved weed management by preventing weed seed germination and blocking emerging seedlings' growth [60].

Ranking	Management
1	Minimizing weed seed rain and the seedbank
2	Rotations
3	Plants versus weeds
4	Pre-crop emergence weeding (tillage)
5	Post-crop emergence weeding
6	Crop, pasture, and livestock choice
7	Sowing, planting, and related techniques
8	Soil conditions
9	Hand weeding

Adapted from Gage and Schwartz-Lazaro [58].

Table 6.
Ranking of hierarchy in integrated weed management (IWM).

6. Unmanned aerial vehicles (UAVs) for organic weed management

In the realm of organic farming, effective weed management poses a unique challenge that requires sustainable and innovative solutions. UAVs have emerged as a transformative tool in this domain, providing organic farmers with precise, efficient, and environmentally conscious methods for weed control. With the advancement in UAV sensors and machine learning techniques in the recent years, use of remote sensing and drones for weed detection and management in organic farms have gained popularity among growers. The UAVs equipped with RGB, multispectral, thermal, and hyperspectral sensors offer organic farmers a powerful means to assess various vegetation parameters crucial for weed management at multiple temporal and spatial scales [61]. These sensors provide high spatial resolutions, enabling the creation of detailed weed maps [62]. Remote sensing technology facilitates a comprehensive analysis of spatial variations in weed populations, allowing for targeted interventions.

The affordability and enhanced flight efficiency of consumer drones make them particularly well-suited for organic farming practices. While advanced sensors such as hyperspectral and LiDAR can be valuable, cost-effective options like RGB cameras are practical for smaller-scale organic operations with limited budgets [63]. Drones play a pivotal role in enabling precise crop monitoring, biomass observation, and weed condition assessment in an organic farm setting. One of the key advantages of UAVs in organic farming lies in their ability to facilitate real-time Site-Specific Weed Management (SSWM) [64]. By employing two-dimensional and three-dimensional sensors coupled with efficient data processing, drones equipped with hyperspectral, multi-spectral, or thermal sensors significantly reduce operational time compared to traditional methods. This efficiency is crucial for organic farmers seeking sustainable alternatives to conventional herbicide spraying. SSWM allows farmers to customize weed management strategies based on specific weed populations within a field [65]. UAVs with precision spraying systems enable targeted weed management in organic agriculture, aligning with principles of minimizing blanket spraying. This approach reduces resource usage and environmental impact, as drones precisely apply site specific organic herbicides. Mattivi et al. presents a noteworthy case study for smart weed control in organic farms. This experimental research used UAVs to autonomously identify the presence of *Sorghum halepense*, *Chenopodium album*, and *Amaranthus retroflexus* in a corn field [66]. Zhang et al. designed a hyperspectral imaging system integrated with a micro-spray heated oil application system to address weed control in young tomato plants. The authors reported that the hyperspectral imaging system accurately recognized 95% of tomatoes, 94% of black nightshade, and 99% of pigweed [67].

The fundamental approach to weed discrimination using UAVs involves identifying spectral regions or vegetation indices maximizing the distinctions between weed and crop plants based on reflectance values obtained from aerial images [68]. Environmental conditions, textural phenotype, and spectral signatures of weeds influence detection and identification. Spectral signatures, representing chemical content in leaves or plants, play a crucial role in evaluating weed identification capacity [69]. For instance, Feyaerts and Van Gool employed an UAV equipped with an RGB sensor and utilized RGB values to calculate a normalized difference vegetation index, enabling the differentiation between crops, such as sugar beets, and weeds [70]. In Perez et al. study, images of cereal fields were analyzed to compute the Normalized Difference Index (NDI) and leaf shape, subsequently employed by Bayesian rule classification and k-Nearest Neighbor algorithms to distinguish cereal plants from weeds [71]. Vrindts et al. took a different approach by using hyperspectral cameras to identify the hyperspectral signatures of crops (sugar beets and maize) and common weeds. They selected specific wavelengths proven significant for crop and weed identification, using these wavelengths as classifiers [72]. These examples suggest that advancement in sensors technologies and next-generation computer vision models for image processing can be exploited for the development of smart weed management techniques in future organic production system.

7. Conclusion

Weed management in organic farming necessitates a holistic and multifaceted approach, considering the diverse strategies available. Tillage practices, mulching, cover crops, crop rotation, and innovative techniques such as allelopathy and biological weed control collectively contribute to sustainable weed control while promoting soil health and biodiversity. It is crucial for farmers to balance the benefits of these practices with potential challenges, ensuring a tailored and integrated weed management plan. Furthermore, the integration of modern technology, such as Unmanned Aerial Vehicles (UAVs), can provide valuable insights into crop health and weed distribution, facilitating precision farming, and enhancing the efficiency of weed management strategies. The ongoing exploration of advanced tools and techniques alongside traditional weed control practices is essential for developing resilient and environmentally friendly weed management systems in organic agriculture.

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Chapter 4

Perspective Chapter: Why Are Compositae Weeds More Invasive?

Heng Yang and Jieshi Tang

Abstract

Biological invasion is a global ecological problem, and it is important to understand the mechanism of successful invasion for the prevention and control of invasive weeds. Based on my experience and expertise in ecology, I have observed a significant gap in the literature regarding Compositae weeds invasions, and aimed to address this gap. We searched the literature related to Compositae weeds invasions published after 2000 in the China National Knowledge Infrastructure, PubMed, Scopus, Embase, and Web of Science. A list of 60 major Compositae weeds that are widely invasive around the world, and five important reasons (reproductive strategies, ecological adaptations, genetic diversity, enemy release, and human activities) explored that could be responsible for the powerful invasiveness of Compositae weeds. We offer a comprehensive overview of the current state of knowledge in this field and present a different perspective that incorporates existing theories. A clear address about the aggressive invasiveness of invasive species belonging to Compositae, and proposing scientific prevention, control, and management strategies will help prevent further invasion around the world in the future.

Keywords: biological invasions, Compositae weeds, reproductive strategies, ecological adaptations, genetic diversity, enemy release, human activities

1. Introduction

Invasive weed species pose a significant threat to global ecosystems and economy around the world [1]. Compositae weeds have been particularly successful at invading heterogeneous habitats, many species within this family have become invasive in various regions (**Table 1**, contains references [2–61]), especially in agroecological zones and grassland areas [62, 63]. Here, we aim to explore the factors that contribute to the strong invasiveness of Compositae weeds. Several reasons for their success in invading new habitats will be discussed, including their reproductive strategies, ecological adaptations, genetic diversity, enemy release, and the impacts of human activities on their spread (**Figure 1**). Understanding these factors can aid in the development of effective management strategies for controlling the invasion of Compositae weeds.

Compositae weeds are recognized for their invasive tendencies, presenting significant challenges such as decreased biodiversity and habitat degradation [64]. These invasive plants possess traits like rapid growth, prolific seed production, and adaptability to various environmental conditions, which enable them to outcompete native

Compositae weeds	Common name	Place origin	Invasive habitats	References
Ageratina adenophora	sticky snakeroot	Mexico	sparse vegetation, bare land	Poudel et al. [2]
Ageratum conyzoides	tropical whiteweed	Tropical America	valley, understory, meadow, wasteland	Erida et al. [3]
Ambrosia artemisiifolia	annual ragweed	Central and North America	roadside, channels, riverbanks, streets	Gusev et al. [4]
Ambrosia trifida	great ragweed	North America	fields, roadsides, wetlands	Xu et al. [5]
Aster subulatus	annual saltmarsh aster	North America	roadside, abandoned land, wilderness	Xu et al. [6]
Bidens alba	common beggar's tick	Tropical America	villageside, roadside, wasteland	Wang et al. [7]
Bidens frondosa	devil's beggartick	North America	wet field	Min et al. [8]
Bidens pilosa	hairy beggarticks	America	villageside, roadside, wasteland	Li et al. [9]
Chromolaena odorata	Siam weed	Mexico	hilly land, savanna	Xu et al. [10]
Erigeron annuus	annual fleabane	North America	hillsides, roadsides, fields	Huang et al. [11]
Erigeron canadensis	horseweed	North America	wilderness, wasteland, field edge, roadside	Liendo et al. [12]
Erigeron sumatrensis	fleabane daisy	South America	meadow, wilderness, roadside	Maslo et al. [13]
Flaveria bidentis	bristly yellowtop	South America	wilderness, pasture, abandoned farmland	Dai et al. [14]
Mikania micrantha	American rope	Central and South America	forest, farmland	Jiang et al. [15]
Parthenium hysterophorus	famine weed	Tropical America	open land, roadside, riverside, slopes	Ullah et al. [16]
Praxelis clematidea	fleabane	South America	roadside, wasteland, farmland, grassland	Intanon et al. [17]
Solidago canadensis	Canada goldenrod	North America	river beach, wasteland, roadside, farmland side	Tian et al. [18]
Tithonia diversifolia	tree marigold	Mexico	river beach, roadside, farmland	Jiao et al. [19]
Ageratum houstonianum	flossflower	Tropical America	forest edge, riverside, farmland, grassland	El Hadidy et al. [20]
Crassocephalum crepidioides	redflower ragleaf	Africa	underwood, bushes, beside ditches	Xie et al. [21]
Erigeron bonariensis	Brazilian fleabane	South America	roadside, river embankment, hillside, countryside	Qasem et al. [22]

Compositae weeds	**Common name**	**Place origin**	**Invasive habitats**	**References**
Galinsoga parviflora	gallant soldier	South America	roadside, open space	Ripanda et al. [23]
Galinsoga quadriradiata	gallant soldier	Mexico	forest, roadside	Liu et al. [24]
Sphagneticola trilobata	wedelia	Tropical America	seaside, waterside, limestone areas	Zhang et al. [25]
Xanthium italicum	Italian cocklebur	Europe, North America	wasteland, waterside, farmland	Shi et al. [26]
Xanthium spinosum	spiny cocklebur	America	roadside, wasteland, farmland	Dudás et al. [27]
Bidens bipinnata	Spanish needles	America	wastelands, hillsides, fields	Zhuang et al. [28]
Coreopsis lanceolata	lanceleaf coreopsis	USA	woods, mountains	Kim et al. [29]
Cosmos sulphureus	sulfur cosmos	Mexico	pastoral, sandy land	Liu et al. [30]
Cyclachaena xanthiifolia	giant false ragweed	North America	highway, the manure pile	Abramova & Nurmieva [31]
Erigeron philadelphicus	Philadelphia fleabane	North America	roadside, wilderness, hillside, orchard, forest	Xu et al. [32]
Tagetes minuta	wild marigold	Tropical America	alpine areas	Moghaddam et al. [33]
Tagetes patula	French marigold	Mexico	grassland, forest, garden	Prebeg et al. [34]
Tragopogon dubius	western salsify	Central Asia, Europe	river beach, wasteland, field edge	Jordon-Thaden et al. [35]
Xanthium mongolicum	Mongolian cocklebur	Mexico	roadside, ditchside, field edge, grassland	Han et al. [36]
Cichorium intybus	chicory	Europe, West Central Asia, North Africa	wasteland, prairie, field, slope	Gazwi et al. [37]
Eclipta prostrata	false daisy	America	riverside, fieldside, roadside	Timalsina & Devkota [38]
Erechtites hieraciifolius	pilewort	Tropical America	understory, hillsides, shrubs, wetlands	Hung et al. [39]
Erechtites valerianifolius	American burnweed	Tropical America	fieldside, roadside	Funez et al. [40]
Glebionis carinata	corn marigold	Morocco	pastoral, wasteland	Mircea et al. [41]
Helianthus tuberosus	Jerusalem artichoke	North America	ruins, houseside, roadside	Phongphan et al. [42]
Senecio vulgaris	common groundsel	Europe	grassland, hillside, roadside	Ebadi & Eftekharian [43]
Silybum marianum	milk thistle	West Asia, North Africa, Southern Europe	open space, wasteland, roadside	Hossain et al. [44]
Soliva anthemifolia	annual sowthistle	South America	wasteland, field	Ghoshal et al. [45]

Compositae weeds	Common name	Place origin	Invasive habitats	References
Sonchus asper	prickly sowthistle	Europe, the Mediterranean	hillside, forest edge, waterside	Sidhu et al. [46]
Sonchus oleraceus	common sowthistle	Europe,d the Mediterranean	forest, field, open space	Choudhary et al. [47]
Taraxacum officinale	dandelion	Europe	grassland, forest, field, roadside	Watanabe et al. [48]
Zinnia peruviana	Peruvian zinnia	Mexico	hillside, grass, roadside	Mohamed et al. [49]
Acanthospermum hispidum	bristly starbur	South America	flat slopes, riversides, ditchsides, roadsides	Sukholozova et al. [50]
Acmella oleracea	paracress	South America	fieldside, roadside	Kato-Noguchi et al. [51]
Anthemis arvensis	corn mayweed	Europe	roadside	Wozniak et al. [52]
Anthemis tinctoria	yellow chamomile	Europe	parks, fields	Orlando et al. [53]
Aster subulatu var. cubensis	Cuban aster	Caribbean	seaside, wetland	Cheng et al. [54]
Calyptocarpus vialis	straggler daisy	Cuba, Mexico and the United States	wilderness, cultivated land, roadside, houseside	Lal et al. [55]
Centaurea cyanus	cornflower	Europe	wasteland, field	Palma-Bautista et al. [56]
Centaurea diffusa	diffuse knapweed	West Asia, Europe	wasteland, field	Keever et al. [57]
Centaurea maculosa	spotted knapweed	Europe	wasteland, field	Mummey et al. [58]
Coreopsis basalis	goldenmane tickseed	North America	parks, gardens	Crawford & Smith [59]
Coreopsis grandiflora	large-flowered tickseed	USA	wasteland, mountains	Huang et al. [60]
Coreopsis tinctoria	golden tickseed	USA	wasteland, mountains, field	Jiang et al. [61]

Table 1.
Informations on the 60 most important species of Compositae weeds.

vegetation and dominate ecosystems [65]. The spread of invasive Compositae weeds is facilitated by human activities, habitat disturbances, and the absence of natural predators in new habitats [66]. Effective control measures, including mechanical removal and targeted herbicide application, are essential to manage their invasion and safeguard native ecosystems from further disruption [67, 68].

Compositae weeds display a wide range of life forms, including annuals, biennials, and perennials [69]. They are characterized by their composite flower heads, which consist of multiple individual flowers on a single head [70]. Compositae weeds have become widely distributed around the world due to their excellent adaptability to different environments and their high reproduction rates [71]. As a result, many species within this family have been introduced to new areas, where they often outcompete and displace native species [72]. For example, Italian cocklebur (**Figure 2**). Understanding the reasons behind their invasiveness is crucial for effective management and conservation practices.

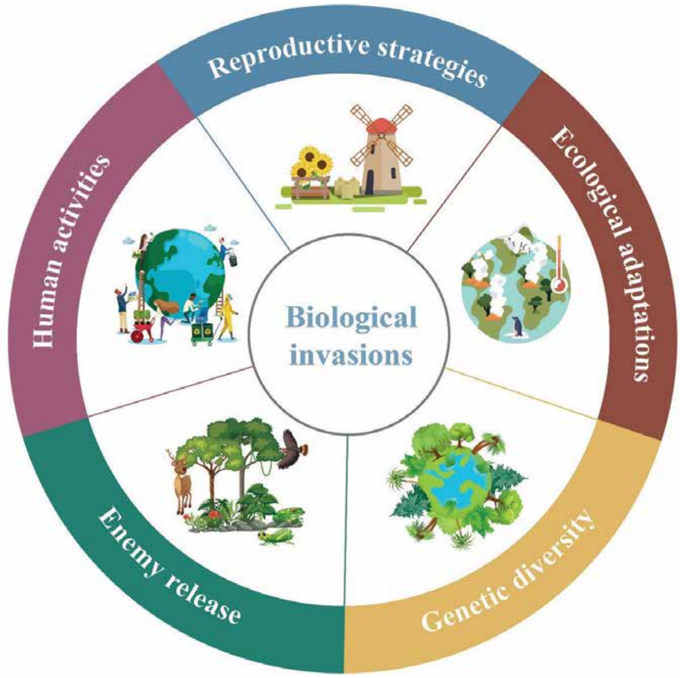

Figure 1.
Main reasons for the global invasion success of Compositae weeds. Five important reasons can be responsible for explaining the strong invasiveness of Compositae weeds, including reproductive strategies, ecological adaptations, genetic diversity, enemy release, and human activities.

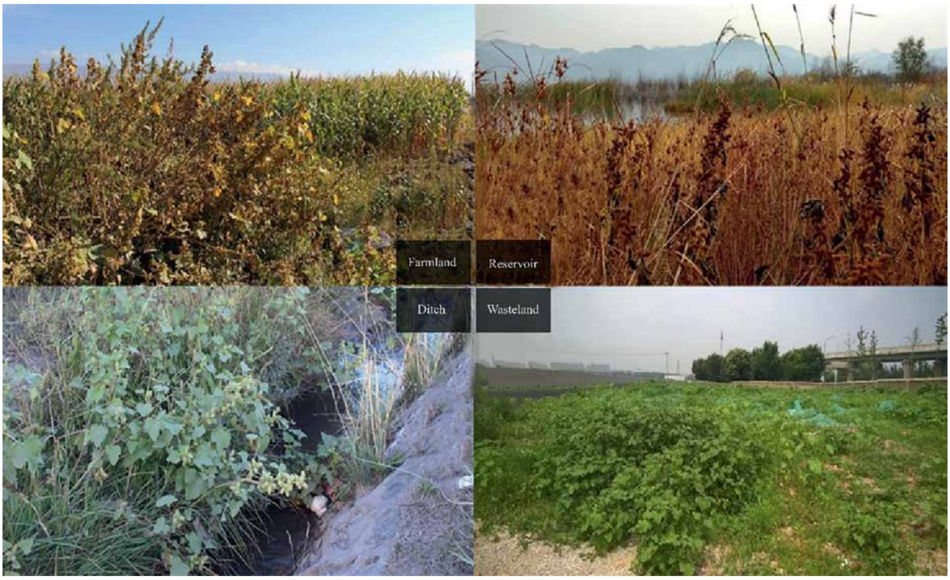

Figure 2.
The current invasion status of Compositae plant X. italicum in China. Four habitat types can be invaded by the alien Compositae plant X. italicum, including farmland, reservoirs, ditches, and wasteland.

2. Methodology

The China National Knowledge Infrastructure, PubMed, Scopus, Embase, and Web of Science search engines were used in the literature collection [73]. Only journal articles and reviews that were published English after 2000 in this study [74]. The search terms and strategies are as follows: TS = ("biological invasions*") OR TI = ("Compositae/Asteraceae weeds*") OR TI = ("strong invasiveness*") OR TI = ("successful invasion*") [75].

3. Reasons for the strong invasiveness of Compositae weeds

3.1 Reproductive strategies

One of the key factors contributing to the invasiveness of Compositae weeds is their unique reproductive strategies. Many species within this family produce large quantities of small, lightweight seeds that are easily dispersed over long distances by wind or water [76]. Additionally, their ability to asexual reproduction, self-pollinate, and insect pollination allows them to rapidly colonize new habitats [77]. These reproductive characteristics provide Compositae weeds with a competitive advantage, allowing them to establish and dominate over other native weed species. Such as *Ambrosia artemisiifolia*, *Solidago Canadensis*, and *Ageratina adenophora*.

3.2 Ecological adaptations

Compositae weeds exhibit various ecological adaptations that contribute to their invasiveness. They are known for their ability to thrive in disturbed habitats, such as roadsides, fields, and forests. Their wide tolerance to different soil types, pH levels, and moisture conditions also enables them to occupy diverse ecological niches [78]. Furthermore, Compositae weeds often possess allelopathic compounds that inhibit the growth of neighboring weeds, further enhancing their ability to outcompete native species [79]. Such as *Helianthus annuus*, *Senecio jacobaea*, and *Acroptilon repens*.

3.3 Genetic diversity

Genetic diversity plays a crucial role in the invasiveness of Compositae weeds. Species within this family often have high genetic variability, which allows them to adapt to new environments and overcome biotic and abiotic stresses [80]. This genetic diversity also increases the chances of hybridization and the formation of novel genotypes with increased invasiveness. Additionally, the presence of polyploid species within Compositae contributes to their ability to occupy new habitats and rapidly expand their range, such as *Conyza bonariensis*, *Erigeron philadelphicus*, and *Conyza canadensis*.

3.4 Enemy release

In their native range, Compositae weeds coexist with specialized herbivores, diseases, and pathogens, regulating their population growth [81]. However, when introduced to new geographic regions, they often escape from their natural enemies, enabling population growth without significant constraints. This lack of natural enemies can lead to uncontrolled proliferation and invasion of Compositae weeds, posing a threat to native biodiversity, such as *Cirsium vulgare*, *Solidago canadensis*, and *Ambrosia artemisiifolia*.

3.5 Human activities

Human activities such as agriculture, horticulture, and international trade have significantly facilitated the spread of Compositae weeds [82]. For example, their introduction as ornamental weeds has resulted in accidental escapes and subsequent invasions in many parts of the world. Furthermore, the disturbance of natural ecosystems through land clearing, urbanization, and climate change creates favorable conditions for the establishment and spread of invasive Compositae species [83]. Prevention measures to control their introduction and spread should be implemented to minimize their impact on native biodiversity, such as *Acroptilon repens*, *Ambrosia artemisiifolia*, and *Solidago canadensis*.

4. Future management strategies of Compositae plant invasions

Effective management strategies for controlling invasive weeds typically involve a combination of prevention, early detection, eradication, and ongoing monitoring. Prevention efforts include implementing strict regulations on the importation and sale of potentially invasive Compositae species, as well as raising public awareness about the risks associated with introducing non-native Compositae plants into natural ecosystems [84].

Early detection is crucial for addressing invasive Compositae weeds before they become established and widespread. This involves training volunteers and professionals to identify invasive Compositae plants and implementing surveillance programs to quickly detect and respond to new invasions [85].

Eradication methods vary depending on the invasive Compositae species and the extent of the invasion but may include mechanical methods such as hand-pulling, mowing, or cutting, as well as chemical control methods like herbicide application. Biological control, using natural enemies such as insects or pathogens to suppress invasive Compositae weeds, can also be an effective long-term strategy when implemented carefully to minimize unintended consequences [86–89].

Ongoing monitoring and management are essential to prevent the re-establishment and spread of invasive Compositae plants. This includes regular surveys to detect and treat new invasions, as well as restoration efforts to rehabilitate areas impacted by invasive weeds and promote the recovery of native plant communities [90].

Collaboration among government agencies, land managers, researchers, and the public is critical for successful invasive Compositae weeds management. By implementing integrated and adaptive management approaches, we can work toward reducing the impact of invasive Compositae weeds and preserving the health and biodiversity of our local ecosystems, especially in agricultural production areas [91].

5. Conclusions

Here, we present a list of the 60 most important Compositae invasive weeds around the world and discuss the reasons why they are so invasive. The aggressive invasiveness of Compositae weeds can be attributed to a combination of factors such as their reproductive strategies, ecological adaptations, genetic diversity, enemy release, and the influence of human activities. Understanding the mechanisms driving their invasiveness is essential for managing and controlling the spread of these species. Further research is needed to assess the impacts of different control measures and develop effective strategies to prevent the further spread of invasive Compositae weeds and protect native ecosystems.

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Author contribution statement

H. Yang and J.S. Tang collected the data and H. Yang wrote the manuscript, and J.S. Tang revised the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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Section 2

Perspective Weeds Utilization and Management

Chapter 5

Artificial Intelligence and Agronomy: An Introductory Reflection on Reducing Herbicide Dependence in Weed Management

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Abstract

The crop production sector faces the critical challenge of effectively managing weeds while reducing herbicide dependence, which aligns with environmental and economic sustainability. This chapter explores the shift toward site-specific weed management (SSWM), accelerated by artificial intelligence (AI) and digital technologies. Also, it addresses the often-neglected complexities of weed-seed bank germination. We propose an integrated approach, combining AI-enhanced weed detection, cover crop strategies to limit weed seedling emergence, cost-effective spot spraying, and the application of large language models to enrich decision-making under an integrated weed management (IWM) scheme. This helps ensure varied management tactics and weed resistance prevention. We present findings from our Chilean case study, which provide insights into real-world challenges and successes, and highlight the study's limitations, such as the specific agroecological conditions and limited sample size, which may affect the generalizability of the results to other contexts. We draw comparisons with global AI-driven weed management advancements. This chapter underscores the potential of such integrated strategies to lower herbicide reliance and contribute to sustainable, technologically advanced weed control, fostering environmental stewardship and economic viability in the face of climate change.

Keywords: integrated weed management, artificial intelligence, site-specific weed management, precision agriculture, herbicide reduction, cover crops, weed detection, weed germination, sustainable

1. Introduction

The challenge of managing agricultural weeds is rapidly evolving, increasingly intersecting with the critical needs for environmental sustainability and economic efficiency. Traditional methods, heavily reliant on broad-spectrum herbicide applications, face growing scrutiny. These methods have raised concerns due to their significant ecological, health, and economic implications [1]. Within this dynamic and challenging landscape, the introduction of artificial intelligence (AI) and digital technologies marks a pivotal shift, offering an opportunity for innovation in weed management strategies [2].

As weeds regularly present a spatial distribution or clusters on fields, site-specific weed management (SSWM) [3, 4], a concept deeply rooted in precision agriculture principles, is at the forefront of this transformation. SSWM advocates for applying the necessary weed control measures precisely where and when they are needed, thus ensuring optimal use of inputs [5, 6]. By leveraging the capabilities of AI and digital technologies, SSWM promises a targeted approach to weed control, significantly reducing herbicide use and minimizing environmental impacts [3]. However, the journey toward the effective implementation of SSWM is fraught with challenges, mainly due to the resilience of weed seedbanks and the swift germination rates of weed seedlings, which pose substantial barriers to effective management using localized treatments [4].

The above-described elements are introduced into an integrated weed management (IWM) framework [7]. This synergistic approach blends the strengths of AI-enhanced weed detection, the ecological benefits of cover crops, and the precision afforded by spot spraying technologies. SSWM into IWM not only aims to curtail herbicide reliance but also ensures the maintenance of effective weed suppression, thereby striking a delicate balance between agricultural productivity and sustainability [5].

Another important aspect we consider is addressing the complexities of IWM, especially in the context of commonly limited access to expert guidance in weed science to the grower; this chapter delves into the emerging role of large language models (LLMs). With their profound ability to process and interpret extensive datasets, LLMs emerge as indispensable allies in the quest for enhanced decision-making within IWM frameworks. They have the potential to give growers nuanced insights, enabling more informed and precise agricultural decisions.

Empirical evidence from a pioneering case study in Chile highlights AI's tangible potential in detecting weeds and leveraging cover crops to mitigate weed pressures. This exploration offers invaluable insights into the practical application and effectiveness of AI-driven weed management strategies, shedding light on the real-world challenges and triumphs of embracing such innovative technologies [7].

A comparative analysis with global advancements draws a comprehensive landscape of AI's current and potential future in agronomy. This examination showcases global progress and delineates the challenges and opportunities on the horizon, underscoring the indispensable need to weave technological innovation with agronomic expertise [8, 9].

The chapter is structured as follows: Section 2 provides background and rationale on the prevalence and impact of weeds, the implications of herbicide overreliance, and an introduction to integrated weed management (IWM). Section 3 discusses the advancements in AI for agronomy, including deep learning and computer vision techniques. Section 4 delves into site-specific weed management (SSWM) and its integration with digital technologies. Section 5 explores spot spray technology's role in advancing precision weed management. Section 6 outlines the conditions for establishing SSWM, including weed population reduction, seed bank management strategies, and the utilization of cover crops. Section 7 examines the potential role of large language models (LLMs) under an integrated weed management (IWM) scheme. Finally, Section 8 discusses future directions and challenges in AI-driven weed management.

2. Methodology

2.1 Literature search and selection

For this chapter, a comprehensive literature search used the customed search agents "Consensus" and "SciSpace" operating in the ChatGPT platform (https://chat.openai.com/). In addition, the AI-driven assistant software Scite (https://scite.ai/assistant) was used. The keywords used for the search included terms related to weed management, artificial intelligence, precision agriculture, and cover crops, as mentioned throughout the chapter. The criteria for paper selection involved relevance to the research topic, publication in peer-reviewed journals, and the presentation of original research findings or significant reviews. Papers that did not meet these criteria or were not published in English were excluded from the analysis.

2.2 Weed detection methodology

For weed detection presented in Section 6.4.2, YOLO (You Only Look Once) v4 models were employed [10]. These state-of-the-art deep learning models were trained on a dataset of annotated images capturing various weed species and crop types under different environmental conditions. The models were optimized for accuracy and real-time performance, enabling precise weed identification and localization within the field. The detected weed instances were then used to generate high-resolution weed density maps, which served as the basis for targeted weed management interventions.

2.3 Cover crop trials

A field trial was conducted to assess the effectiveness of cover crops in suppressing weed growth and reducing weed seed bank levels (Section 7.5). The cover crop selected for this study was rye (Secale cereale), cultivated from May 2023 to December 2023 on a one-hectare plot near Chillan city, Chile. Two nitrogen fertilization treatments were applied: a high rate (150 kg N/ha) and a low rate (50 kg N/ha). The cover crop was terminated at two growth stages: the tillering stage (using glyphosate application) and the anthesis stage (using a roller-crimper). Weed pressure, assessed as the density of weed seedlings per square meter, was evaluated before cover crop termination and at regular intervals after the establishment of the subsequent cash crop. The data collected were subjected to statistical analysis to determine the significance of differences in weed pressure among the treatments.

3. Background and rationale

3.1 Prevalence and impact of weeds in agriculture

The prevalence of weeds within agricultural contexts significantly hampers crop yields, necessitating the development of robust weed management strategies. The complexity of these challenges varies across different agricultural ecosystems, highlighting the need for dynamic management approaches. Studies comprehensively review the global weed spectrum and its evolving challenges, illustrating the dynamic nature of weed interactions within agricultural ecosystems [11, 12]. Different weed species present distinct challenges, competing with crops for resources, engaging in allelopathy, and serving as vectors for pests and diseases. For example, the presence of *Chenopodium album* in cornfields can result in yield reductions of up to 40%, showcasing the aggressive competition for nutrients, light, and water [13]. Similarly, *Glycine max*, often termed volunteer soybean when it grows outside its intended cultivation area, can diminish soybean yields by approximately 35%, underscoring the complexities of managing weeds closely related to the crops [14].

The impact of weeds varies depending on the crop type, environmental conditions, and weed density. A comprehensive analysis of how environmental factors influence weed-crop interactions emphasizes the importance of timely weed management [15]. Furthermore, the stage of weed emergence in the crop plays a crucial role in the level of competition and potential yield loss, with early emerging weeds posing significant threats to crop establishment [16].

This situation underscores the need for an integrated approach to weed management. Traditional methods primarily focused on chemical control are increasingly complemented by integrated weed management (IWM) strategies that incorporate ecological and biological aspects of weed control. Reviews stress the significance of adopting a holistic and sustainable combination of cultural, mechanical, biological, and chemical methods [16, 17]. The move toward IWM signifies a growing awareness of the necessity for environmentally sustainable and economically viable weed control strategies.

3.2 Environmental, economic, and social implications of herbicide usage

Using herbicides while effectively controlling weeds carries significant environmental, economic, and social implications. From an environmental standpoint, herbicides contribute to soil degradation, water pollution, and harm to non-target plant and animal species [18]. Economically, herbicide dependency escalates farmers' costs, particularly when faced with herbicide-resistant weed strains. Socially, there are heightened health concerns for consumers and agricultural workers exposed to these chemicals, prompting a reevaluation of the long-term sustainability of intensive herbicide use [19].

3.3 Introduction to integrated weed management (IWM) and its significance

Integrated weed management (IWM) marks a pivotal shift in confronting these challenges. IWM adopts a comprehensive approach encompassing various weed control techniques, including mechanical, cultural, biological, and chemical strategies [20, 21]. Selecting specific weed management approaches within an IWM framework depends on the weed species present, crop type, environmental conditions, and available resources [22]. Its importance stems from its ability to lessen the dependency on herbicides, thereby mitigating their environmental, economic, and social impacts [23]. Furthermore, IWM seeks to bolster the sustainability of agricultural operations by promoting biodiversity, enhancing soil health, and maintaining the long-term ecological equilibrium of farming ecosystems [24].

4. Advancements in artificial intelligence for agronomy

Integrating AI into agronomy, the science and practice of crop production and soil management, promises a transformative era, offering innovative strategies that enhance precision and sustainability in agricultural practices. AI refers to developing computer systems capable of performing tasks that typically require human intelligence, such as visual perception, speech recognition, decision-making, and language translation. This paradigm shift is particularly evident in the realm of precision agriculture and sustainable weed management, where AI technologies have the potential to revolutionize traditional approaches [25]. Despite a growing number of studies, there are few practical applications at the farming level [26].

AI technologies are increasingly important in advancing agronomy, providing sophisticated solutions that range from crop monitoring to disease detection and resource optimization. At the forefront are machine learning (ML) and deep learning (DL) algorithms, which have the potential to contribute significantly to the precision and efficiency of agricultural practices. These algorithms, capable of analyzing extensive and complex datasets, enable the prediction of crop health and the detection of diseases with remarkable accuracy, facilitating targeted interventions that enhance crop management while minimizing the need for chemical inputs. Deep learning, employing convolutional neural networks, has been critical in extracting accurate information from complex images, marking a revolution in field application developments during the last decade. The application of computer vision technology, which, through drone and satellite imagery, allows for the early detection of anomalies and opens the possibility for targeted management strategies that significantly reduce herbicide use, paving the way for more sustainable agricultural practices [27, 28].

The advent of robotics and autonomous systems represents another potential leap toward the automation of agricultural practices. These systems, powered by AI, undertake various tasks, including planting, harvesting, and precise weed control, thus reducing labor costs and minimizing chemical dependencies [29]. Furthermore, predictive analytics, driven by AI models, offer valuable insights that assist farmers in making well-informed decisions. This predictive capability supports optimizing resource use and maintaining crop health, showcasing AI's potential to impact agricultural outcomes significantly [30].

Several impactful case studies demonstrate the practical application of AI in agronomy. Precision farming projects employing AI-driven drones and sensors have markedly reduced the indiscriminate application of herbicides by accurately identifying areas requiring treatment [31]. Additionally, AI for pest detection has facilitated the development of systems capable of early pest infestation detection. Through machine learning algorithms, automated systems enable targeted pest control measures that significantly reduce chemical treatments [32]. Large language models (LLMs, i.e., adjusted versions of ChatGPT by OpenAI or Claude by Anthropic) promise to revolutionize agricultural extension services by providing real-time, customized advice to farmers, enhancing productivity and sustainability [33].

While AI presents significant opportunities for agronomy, its widespread integration encounters clear technical obstacles. The primary challenges are the high costs of implementing AI solutions and the complexity of these technologies, which can inhibit their adoption across the agricultural sector [34]. Furthermore, the necessity for stringent data privacy and security measures demands the establishment of comprehensive data governance frameworks to safeguard sensitive agricultural data [35]. As an example, an essential component of effectively applying AI within agriculture is ensuring compatibility between AI systems and existing agricultural infrastructure. In this way, the success of AI applications relies on their ability to seamlessly integrate with current practices, highlighting the need for interoperability and standardization [36]. Addressing these technical challenges is vital for leveraging AI to improve agricultural efficiency and sustainability.

5. Site-specific weed management and AI-driven precision weed control

5.1 SSWM background

Site-specific weed management (SSWM) strategically employs herbicides for precise weed control, enhancing efficiency while minimizing environmental impacts and safeguarding non-target species [37]. This concept started with photoelectric diodes in the 1970s and 1980s and evolved through the 1990s with the adoption of machine learning and camera technologies for refined weed identification [38]. Nowadays, some SSWM initiatives incorporate advanced methods such as laser and electrical weeding, capitalizing on computer vision and deep learning with deep convolutional neural networks (CNN) for unparalleled precision in weed detection.

The role of artificial intelligence (AI) in SSWM is transformative, significantly enhancing weed detection and identification accuracy through advanced machine learning algorithms and computer vision techniques. This precision allows for targeted herbicide application directly onto weeds, substantially reducing broad-spectrum herbicide use [39]. Consequently, this focused strategy not only diminishes herbicide consumption but also mitigates the emergence of herbicide-resistant weed strains [40]. Thus, AI-driven SSWM represents a harmonious blend of technological innovation and environmental stewardship, establishing a new standard for sustainable and cost-effective weed management practices.

5.2 Integration of digital technologies

Digital technologies, including drones, sensors, and geographic information systems (GIS), are integral to SSWM, bolstering real-time monitoring and decision-making capabilities [41]. Drones with high-resolution cameras and AI algorithms provide comprehensive field scans, identifying weed infestations with remarkable accuracy [13]. Field-deployed sensors offer valuable environmental data, aiding in predicting weed emergence patterns [42]. GIS applications synthesize these data, producing detailed maps that guide targeted weed control measures, effectively optimizing SSWM strategies [43].

5.3 Advantages of SSWM

SSWM presents numerous advantages over traditional herbicide application methods. It significantly reduces the volume of herbicides needed, decreasing the environmental footprint of weed management and promoting biodiversity and soil health [44]. Economically, SSWM yields considerable savings for farmers by optimizing herbicide usage and reducing labor requirements [43]. Furthermore, SSWM boosts crop yield and quality by eliminating competition with weeds for resources [45].

6. Spot spray technology: advancing precision in weed management

6.1 Theoretical underpinning and significance of spot spray technology

Spot spray technology marks a significant advancement within the site-specific weed management (SSWM) framework. It enables selective herbicide application on weeds, markedly reducing the use of agrochemicals [46]. This development is increasingly critical amid growing calls for environmental conservation and economic efficiency. The fusion of this technology with AI-driven weed detection represents a leap toward achieving unmatched precision and effectiveness in herbicide application [47].

6.2 Technological innovations and their implications for targeted herbicide delivery

The evolution of spot spray technology has seen the introduction of systems equipped with sophisticated sensing and AI algorithms [48]. These innovations facilitate the precise differentiation between crops and weeds, allowing for targeted herbicide applications [49]. The deployment of drones and autonomous vehicles for spot spraying highlights this technology's adaptability and scalability, providing versatile solutions for various agricultural contexts [50].

6.3 Environmental and economic ramifications of spot spray technology adoption

Spot spray technology brings significant environmental benefits, notably reducing herbicide runoff and protecting soil and aquatic ecosystems [51]. Economically, it offers the potential for cost savings through reduced herbicide use and increased crop yields by efficiently managing weed competition. Additionally, it addresses the challenge of herbicide resistance, ensuring the sustainable management of weeds [52].

6.4 AI integrations in Chilean agriculture for weed management

6.4.1 Initiatives to incorporate AI methods to weed management

Since 2021, Chile has embarked on innovative initiatives led by the Instituto de Investigaciones Agropecuarias (INIA) and the Centro Nacional de Inteligencia Artificial (CENIA) and supported by the Ministry of Agriculture. These efforts represent a concerted move toward incorporating artificial intelligence (AI) into agriculture, with a specific focus on leveraging large language models (LLMs) and advanced weed detection technologies. Central to these initiatives is the development and application of AI as the cornerstone for advancing SSWM and associated technological innovations. The agricultural landscape in Chile is markedly diverse, encompassing a broad spectrum of crops across various regions. This diversity, coupled with relatively smaller farm sizes compared to countries like the USA, Argentina, and parts of the European Union, presents unique challenges and opportunities for implementing AI-driven solutions. The initiatives aim to tailor AI technologies to meet the specific needs of Chilean agriculture, ensuring relevance and applicability across different scales and types of farming practices.

Also, a notable challenge in the region is the scarcity of weed science specialists, intensifying the need for innovative, personalized weed management solutions. The shortage of experts in this field has heightened the urgency for deploying AI technologies that can offer scalable, efficient, and accessible support to farmers. The collaborative efforts between INIA and CENIA are directed at filling this critical gap, utilizing AI to democratize access to expert knowledge and decision-support tools in weed management.

6.4.2 First experiences

Efforts have been concentrated on testing methodologies for various weed-crop combinations, image types (aerial or terrestrial), lighting conditions, and the

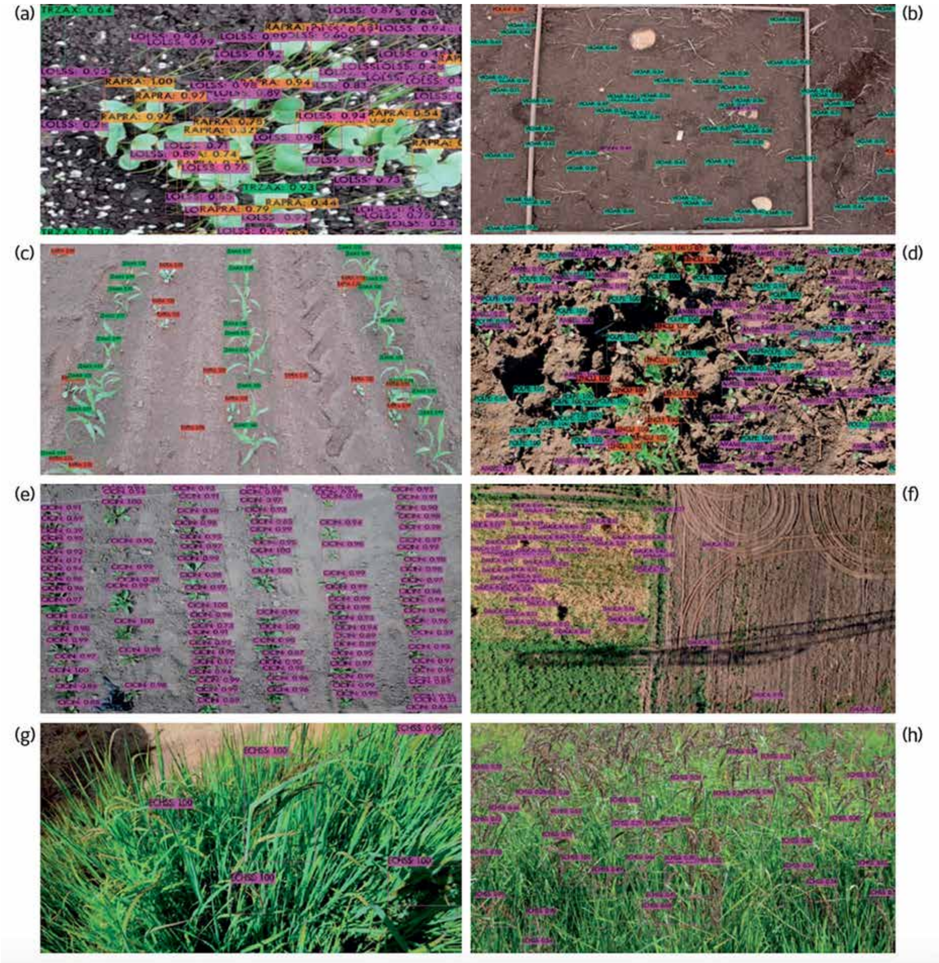

Figure 1.
Weed detection results for models for various crops in Central-Southern Chile: This figure presents representative results of weed detection across different agricultural settings, including (a) wheat fields, (b) autumn chemical fallow, (c) maize cultivation, (d) lentil fields, (e) industrial chicory plants, (f) wild carrot inflorescences, and (g, h) Echinochloa crus-galli inflorescences. Each detection is highlighted with squares, indicating the species identified, accompanied by their respective EPPO codes.

phenological development of the detected plants. This was achieved using deep learning models for object detection. The results indicate that using artificial intelligence models makes it possible to quantify different weed species across diverse environmental and phenological conditions of the populations studied. In these cases, the overall prediction accuracy (F1 score) exceeds 80%, with a peak of 96%. Some images of these predictions are shown in **Figure 1(a–h)**.

Despite these promising results, various aspects require improvement. A primary concern is integrating all versions of the artificial intelligence model into a single or a few models, for example, according to phenological states, capable of predicting across a broader range of weed/crop scenarios. The second challenge is enabling these models to function at machinery operational speeds under field conditions. Progress has been made toward real-time weed detection under variable field conditions and for diverse crop and weed combinations, where more than 24 frames per second can be analyzed (see Video 1, https://drive.google.com/file/d/1zTZml60zujauSTZrt0zbyOhYsSTLfabE/view?usp=drive_link; Video 2, https://drive.google.com/file/d/1CXafkJYgPevsLxVmSSYVhjMxjQIZufKd/view?usp=drive_link; and Video 3, https://drive.google.com/file/d/1N82wKsl4qJasLHNM-2nQW3-eCq7NKBV2/view?usp=drive_link).

The strategic decision to focus on first place on developing computer vision models for SSWM is predicated on their foundational role across various applications, from weed mapping to the operation of site-specific weed control machinery. This emphasis arises from the need for robust databases that capture diverse scenarios of weed and crop interactions and adaptable models for widespread application. Once deployed, these models require iterative fine-tuning to accommodate to new field scenarios, such as changes in crop-weed dynamics, lighting conditions, and phenological stages. Consequently, the initial models will be refined over time, learning and evolving through their operational lifespan. Streamlining this process to ensure robustness and efficiency poses a significant challenge that must be addressed in forthcoming agricultural seasons.

As depicted in **Figure 2**, the progression from model development stages (**Figure 2a–c**) to deployment in specialized field-ready computers (**Figure 2d**) lays the groundwork for the generation of prescriptive maps (**Figure 2e**). This progression also facilitates the integration of these models into machinery equipped for executing SSWM actions in real time within the field (**Figure 2f**). Such advancements signify an advance in SSWM, where machine learning enhances weed management efficacy and becomes a continuous learning process, adapting and improving with each crop cycle.

6.4.3 Next steps

The momentum behind these initiatives in Chile is set to be further propelled by a new project titled “Weed Management Using Artificial Intelligence for Sustainable Agriculture in Wheat, Rice, and Legumes in Chile” (2024–2026), supported by the Foundation for Agrarian Innovation (FIA) agency. The main goal of this project is to develop and implement an AI system for mapping weeds and providing sustainable recommendations and controls, thereby enhancing the efficiency and sustainability of wheat, rice, and legume agriculture in the central-southern zone of Chile. Its specific objectives include:

- Developing AI models that are applicable under our productive conditions for weed recognition.

- Implementing an AI-based weed mapping system.

- Developing a language model trained to give sustainable weed management recommendations.

- Integrating the mapping system and the language model into a user-friendly tool for farmers and service companies.

- Implementing integrated weed management, combining AI mapping, personalized recommendations, and variable control under real conditions.

- Conducting extension and dissemination activities toward farmers, technical assistance services, and service companies.

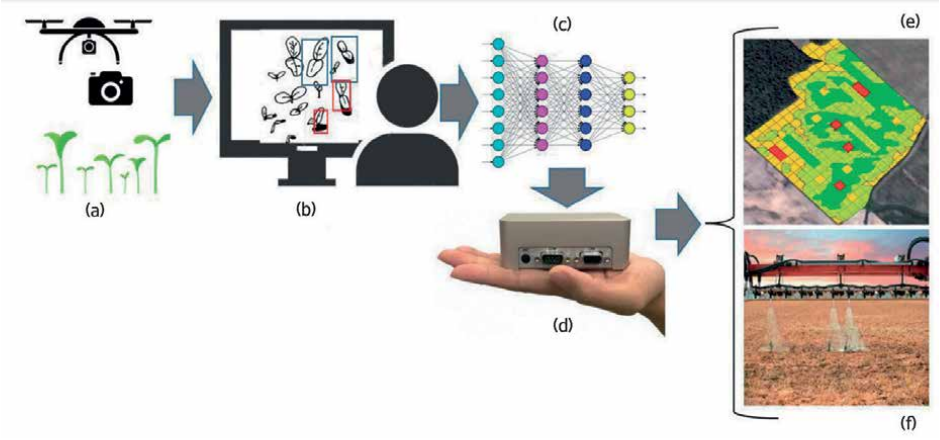

Figure 2.
This schematic illustrates the integrated process of employing computer vision models for site-specific weed management (SSWM), beginning with (a) aerial and terrestrial data acquisition over crops via drones. The workflow progresses to (b) image processing, where computer vision techniques identify weeds. Subsequently, (c) machine learning algorithms, represented by neural networks, learn to distinguish between crops and weeds. The trained model is then deployed on (d) a portable computer tailored for field conditions, which supports generating (e) prescriptive maps for targeted interventions. Finally, (f) machinery equipped with precision spraying technology executes SSWM actions in real time, as directed by the insights gained through advanced AI modeling.

This project embodies a comprehensive approach to embedding AI into Chile's agricultural practices, focusing on critical crops such as wheat, rice, and legumes. By leveraging AI for precise weed detection and management, the initiative aims to revolutionize traditional practices, making them more sustainable and efficient. This endeavor demonstrates the potential for AI to address specific agricultural challenges and sets a precedent for how such technologies can be adapted to different environmental and agricultural contexts. The focus on creating an accessible tool for farmers underscores the commitment to ensuring that these advancements are practical and beneficial at the grassroots level, further contributing to Chile's overarching goal of sustainable agriculture.

Spot spray technology and SSWM use in Chile is part of a worldwide trend toward technologically improved and sustainable weed management methods. This approach emphasizes the significance of precision agriculture in increasing productivity while maintaining a healthy environment. It also underscores the need for global cooperation and knowledge exchange to promote the implementation of AI and SSWM [53].

One of the main topics we consider in our workflow in Chile is the adaptability of future spot spray technology and SSWM in different agricultural settings, which will be vital for its widespread use [11, 54]. The fact that this technology can be customized according to specific management, economic, environmental conditions, and crop species shows its potential for local adaptation.

7. Conditions for establishing site-specific weed management

Identifying and implementing foundational conditions conducive to effective deployment is critical within the SSWM domain. This section presents a part of the strategy necessary for SSWM's successful application, emphasizing the management of weed populations per square meter and the significant role of cover crops within an integrated weed management strategy. These elements are crucial in enhancing the accuracy and efficiency of weed control measures in precision agriculture, a consideration not extensively covered in technical literature.

7.1 Reduction of weed populations per square meter

Reducing weed populations per square meter is pivotal for adopting SSWM strategies. This tactic mitigates immediate competitive stress exerted upon crops and aims to curtail the potential of the weed seed bank, thereby addressing a critical aspect often overlooked in the literature.

From our analysis, addressing this concern is imperative; neglecting to do so could negate the advantages of an SSWM scheme. If weed populations exceed a certain density threshold (e.g., one seedling per square meter), the necessity for blanket application methods may be maintained, as used in traditional weed management approaches. Such a scenario not only diminishes the specificity and efficiency gains offered by SSWM but also incurs increased application costs, potentially detracting from the scheme's appeal and feasibility. Consequently, managing seedling densities per square meter presents an agronomic challenge that necessitates a long-term, holistic perspective, encompassing the entire crop rotation cycle and leveraging all available agronomic tools (cultural, mechanical, etc.) throughout successive growing seasons. In this sense, integrating advanced precision technologies, including drone-assisted surveillance and AI-enabled identification, and, most importantly, proper agronomical management through rotation is vital for effectively managing these populations [55, 56].

Therefore, it is essential to view SSWM and its associated technologies not as standalone solutions but as integral components of an IWM program. Such integration is indispensable, particularly under conditions observed in Chile, where managing cover crops emerges as a promising strategy to alleviate seedling pressure, as detailed in Section 6.5. Incorporating cover crops effectively into IWM schemes underscores the potential to significantly reduce weed seedling emergence, thereby enhancing the efficacy of SSWM strategies in maintaining weed populations below critical thresholds and ensuring sustainable agricultural productivity.

7.2 Weed seed bank management strategies

The weed seed bank poses a significant threat to agronomic productivity by storing seeds capable of causing future infestations. Effective seed bank management involves strategies to reduce seed viability and prevent germination. Techniques such as soil solarization, strategic tillage, and pre-emergent herbicides can be part of a comprehensive approach to minimizing the seed bank's impact [57]. Furthermore, employing models to forecast and model seed bank dynamics can enhance the timing and effectiveness of these strategies [58].

7.3 Cover crops: a dual role in weed and seed bank management

Cover crops play a pivotal role within the SSWM framework, offering dual benefits of weed emergence suppression through competitive exclusion and soil health improvement [52]. Their ability to occupy space and resources deters weed proliferation [43]. Additionally, certain cover crops exhibit allelopathic properties, releasing chemicals that inhibit weed seed germination and growth [59]. Integrating cover crops into crop rotation and management plans highlights their value in comprehensive weed management strategies [60].

7.4 Synergistic integration of cover crops with SSWM

The synergy between cover crops and SSWM techniques significantly enhances weed control efficiency. This combination leverages the ecological benefits of cover crops with the precision and efficacy of SSWM, promoting herbicide reduction and environmental conservation. Digital mapping and AI analyses aid in identifying optimal cover crop species and planting strategies to support specific SSWM practices, providing customized solutions for each farm's unique needs [61].

7.5 Necessity of cover crops implementation in Chile: initial steps

In Chile's primary zone for annual crop production, weed infestation from the seed bank significantly exceeds the thresholds for adopting a site-specific weed management (SSWM) system, with infestations often surpassing 200 plants per square meter in various conditions (**Figure 3a**). This challenge coincides with the urgent need to reduce herbicide applications during the fallow period, especially the use of glyphosate and the excessive reliance on tillage for weed-free soil. In response to these challenges, adopting cover crops has been identified as a strategic initiative to mitigate weed pressure, including annual and complex perennial species previously unutilized in our cropping areas. Cover crops offer a scalable and economically viable strategy that complements the careful use of pre-emergent herbicides.

Trials with winter rye have been initiated to explore the impact of sowing densities (**Figure 3b** and **c**) alongside evaluations of nitrogen fertilization levels (**Figure 3d** and **e**), the termination of cover crops (**Figure 3f**), and the establishment of spring crops (i.e., dry bean, **Figure 3g**) following the cover crop phase.

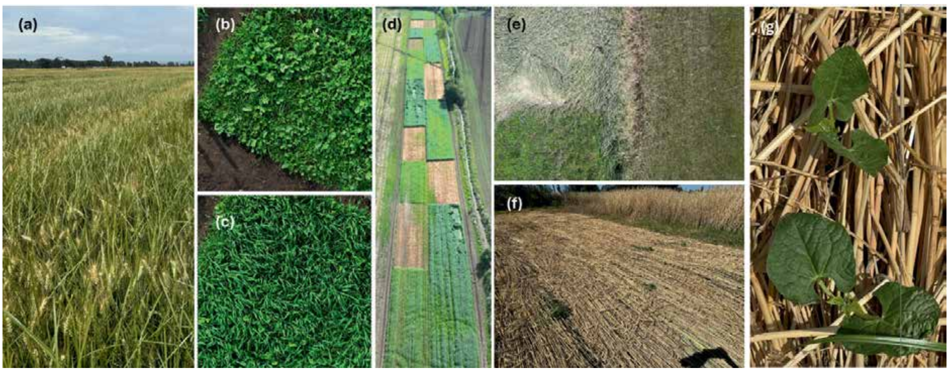

Figure 3.
*(a) High-density weed infestations are common in the irrigated Central Valley of Chile (e.g., Cyperus esculentus in wheat). Initiatives have been launched to incorporate cover crops to reduce the germination weed burden. These initiatives have started with treatments of varying establishment densities, with low densities (e.g., <40 kg of seed/ha) (**Figure 3b**) compared to high densities (e.g., 150 kg/ha of rye), (**Figure 3c**) where a noticeable decrease in weed pressure (Raphanus spp.) was observed in the latter case. Additionally, field experiments using different nitrogen doses (**Figure 3d**) have been conducted, where rye at both high fertilization and lower doses was able to suppress germinating weeds. However, at the high N dose, the rye showed lodging (**Figure 3e**). Finally, initial experiences with terminating the cover crop (**Figure 3f**) and sowing the following spring crop in the rotation (beans, **Figure 3g**) have also been carried out.*

Early results suggested a marked reduction in weed pressure in fields (**Figure 3f** and **g**) that previously faced high weed densities, particularly with problematic species such as *Ambrosia artemisiifolia* and *Cyperus esculentus*. Implementing cover crops within Chile's diverse agricultural landscapes aims to validate their practicality and benefits within the SSWM framework. The goal is to integrate cover crops into Chilean agricultural systems effectively, thereby improving weed suppression, soil structure, and the overall yield and quality of crops [62]. This initiative is expected to highlight the adaptability and efficiency of cover crops and SSWM practices across varied agricultural ecosystems [63–65].

8. Integrated weed management and large language models

8.1 The evolution and impact of large language models in agriculture

The introduction of (LLMs) represents a pivotal advancement in artificial intelligence, significantly impacting various fields, including agriculture [66, 67]. LLMs are defined as deep learning algorithms capable of understanding, generating, and interacting with human language at an unprecedented scale [31]. The global impact of LLMs was notably amplified with the advent of ChatGPT, a variant of the generative pre-trained transformer models, which demonstrated the potential of LLMs to revolutionize not only technology sectors but also industries far afield, such as agriculture [68]. This technology's ability to process and generate text akin to human writing has revolutionized decision-making, predictive analytics, and automation in agricultural practices [69]. Recent developments in LLMs have led to the creation of sophisticated algorithms that interpret complex agricultural data, offering insights and strategies for effective farm management [70–72].

8.2 LLMs' role in weed management strategies

LLMs have the potential to revolutionize weed management strategies by providing intelligent, data-driven solutions to the complex challenges faced in integrated weed management (IWM) and site-specific weed management (SSWM). These advanced AI models can process and analyze vast amounts of data from various sources, such as satellite imagery, weather patterns, soil conditions, and historical weed occurrence records. By leveraging this wealth of information, LLMs can generate highly personalized and context-specific weed control recommendations, tailored to individual farms' unique needs or even specific field sections.

LLMs' ability to provide expert-level guidance is particularly valuable in regions with limited access to weed management specialists. By encapsulating the knowledge and experience of top experts in the field, these models can serve as virtual advisors, offering farmers real-time, actionable insights on the most effective weed control strategies for their specific situations. This empowers farmers to make informed decisions and promotes the wider adoption of IWM and SSWM practices, even in areas with limited access to professional support.

However, it is important to note that the application of LLMs in weed management is still in its early stages. When writing this chapter, researchers and companies are actively exploring and developing prototypes that showcase the immense potential of these models.

Current foundational LL models, such as GPT-3, BERT, and T5, have demonstrated remarkable capabilities in various natural language processing tasks. However, these models are not specifically trained or fine-tuned for the agricultural domain, particularly in weed science. To harness the full potential of LLMs in addressing weed management challenges, it is crucial to adapt these models to the specific language, terminology, and context of agriculture. This requires a collaborative effort between AI researchers and domain experts in weed science to curate relevant datasets, define domain-specific tasks, and fine-tune the models accordingly. By incorporating the knowledge and expertise of weed scientists into developing agricultural-specific LLMs, we can create powerful tools that provide accurate, reliable, and actionable insights for farmers and land managers. This is an urgent task that we, as domain experts, must undertake to bridge the gap between AI advancements and the agricultural community's practical needs, ultimately promoting sustainable and effective weed management practices.

While the current implementations may be limited in scope and scale, the rapid advancements in AI and the growing availability of agricultural data suggest that LLMs will play an increasingly pivotal role in shaping the future of weed management. As these models continue to evolve and mature, they are poised to become indispensable tools for farmers, enabling them to tackle the complexities of IWM and SSWM with unprecedented precision and efficiency [73].

8.3 Addressing agricultural challenges with LLMs

Farmers must navigate a complex web of factors, including unpredictable weather conditions, soil health, pest and disease outbreaks, and market fluctuations, all while striving to optimize crop yields and maintain economic viability. The scarcity of domain experts, particularly in specialized areas like weed science, exacerbates these challenges, leaving many farmers without access to the knowledge and guidance needed to make informed decisions.

This is where LLMs can play a transformative role. By serving as virtual consultants, LLMs can bridge the knowledge gap and provide farmers with the insights and recommendations they need to overcome their myriad challenges. These models can analyze vast amounts of data from multiple sources, including scientific literature, historical records, and real-time sensor data, to generate comprehensive and actionable advice tailored to each farmer's specific circumstances.

By functioning as virtual experts, LLMs can democratize access to specialized knowledge and empower farmers to make data-driven decisions that optimize their operations and mitigate risks. This is particularly crucial in regions where access to agricultural specialists is limited, as LLMs can fill the void and provide farmers with the support they need to navigate the complexities of modern agriculture. As LLMs continue to advance and integrate with other precision agriculture technologies, they can transform farmers' problem-solving and decision-making, ultimately leading to more sustainable, resilient, and productive agricultural systems.

8.4 Future prospects of LLMs in agriculture

The future integration of LLMs within the agricultural sector promises further refinement, with models becoming increasingly customized to address specific farming challenges. Anticipated advancements include the capacity of LLMs to assimilate real-time data, offering dynamic, personalized advice to farmers.

Incorporating LLMs IWM and SSWM heralds a transformative era for agriculture, helping to address its complexities and uncertainties. As these technologies continue to evolve, they are set to play a pivotal role in enhancing sustainable weed management practices, providing vital support to farmers worldwide. This synergy marks a significant stride toward greater efficiency, sustainability, and resilience in agricultural systems.

9. Future directions and challenges

9.1 Emerging trends in AI for weed management

Innovations at the cutting edge of agricultural technology, such as autonomous weed control robots, drone-based surveillance with hyper-spectral imaging, and AI-driven models for predicting herbicide resistance, are redefining the landscape of SSWM. These advancements promise to enhance the precision and efficacy of weed management strategies [74–76].

The merger of blockchain with AI in agriculture introduces a new level of data transparency and traceability, crucial for building trust across the supply chain. This fusion facilitates a cooperative platform for seamless data exchange and informed stakeholder decision-making. It propels agriculture toward a smarter, more sustainable future by enabling precise resource use and enhancing operational efficiency [77].

9.2 Limitations, challenges, and barriers to adoption

Introducing AI technologies and infrastructure comes with high costs, posing substantial challenges, especially for smallholder farmers and those in developing regions. Furthermore, the inherent complexity of AI systems necessitates specialized knowledge and extensive training [78, 79].

The lack of structured and comprehensive databases hinders the widespread adoption of large language models (LLMs) and computer vision models in weed science. LLMs require high-quality, domain-specific data to generate accurate insights, while vision models rely on large amounts of labeled images to effectively learn and classify weed species. However, in weed science, there is a scarcity of well-organized and easily accessible datasets that can be used to train and fine-tune these models.

Developing robust LLMs and vision models for weed management necessitates a rich corpus of data encompassing various aspects of weed biology, ecology, and control strategies. Without such comprehensive datasets, these models may struggle to provide reliable and context-specific recommendations to farmers and land managers.

Collaborative efforts among weed scientists, data experts, and AI researchers are crucial to address this limitation. Building and curating structured databases involves collecting, organizing, and annotating data from diverse sources, such as field experiments, remote sensing, and farmer observations. Standardizing data formats and creating user-friendly interfaces for data access and contribution can further facilitate the development of tailored LLMs and vision models.

Establishing data-sharing protocols and incentives for researchers and institutions to contribute to these databases can accelerate the growth and refinement of these resources. By fostering a culture of open data and collaboration within the weed science community, we can create a robust foundation for developing accurate and reliable models that revolutionize weed management practices.

9.2.1 Out-of-domain problem in DL models

From our point of view, addressing the out-of-domain (OOD) problem will be crucial when incorporating AI models into IWM schemes, where deep learning (DL) models often encounter data vastly different from what they were trained on. This discrepancy, particularly pronounced due to the diverse and unpredictable nature of agricultural environments, can significantly impair the models' performance. For instance, an AI system trained to identify specific weed species might struggle when presented with images or conditions it has not seen before. To overcome this challenge and enhance model reliability, it is essential to develop generalist models. These models are designed to adapt flexibly to new situations by drawing on a broad and varied dataset and incorporating robust architectures to changes. Doing so ensures accuracy across various agricultural scenarios, ensuring effective decision-making and operational efficiency [80].

9.2.2 Finetuning models for dynamic agricultural environments

Given the dynamic nature of agricultural operations, there is a pressing need for the ongoing and efficient finetuning of DL models to ensure their rapid adaptability to changing conditions. Initiatives like the current FIA-Chilean project, "Weed management with the use of artificial intelligence for sustainable agriculture in wheat, rice, and legumes in Chile", showcase innovative methods to increase data labeling efficiency and enhance model adaptability.

10. Conclusions

This chapter explores the critical challenge of effective weed management while reducing herbicide dependence in crop production. We propose a shift toward AI-driven site-specific weed management (SSWM) as a promising approach to address this challenge.

Our research emphasizes the importance of considering weed-seed banks and seed germination in weed management. We present an integrated approach combining AI-enhanced weed detection, cover cropping, spot spraying, and large language models (LLMs) to ensure varied management tactics and prevent herbicide resistance.

Our Chilean case study provides insights into the real-world implementation of AI-driven SSWM, demonstrating its potential in enhancing weed management and reducing herbicide reliance despite limitations in generalizability due to specific agroecological conditions and limited sample size.

This chapter compares global advancements and underscores the transformative potential of integrated strategies combining AI, precision agriculture, and ecological approaches for sustainable and adaptable weed control in the face of climate change.

However, adopting AI-driven SSWM faces challenges, such as high initial costs, lack of structured databases, and the need for collaboration between AI researchers and weed science experts to fine-tune AI models.

In conclusion, despite limitations and challenges, AI-driven SSWM has significant potential in revolutionizing weed management. An integrated approach combining

AI, precision agriculture, cover cropping, and ecological principles can lead to more sustainable and effective weed control strategies. Stakeholders must collaborate and invest in making these technologies and practices more accessible and adaptable to diverse farming contexts, contributing to a more sustainable and resilient future for crop production.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 6

Transforming Weeds to Edible Vegetables: An Alternative Sustainable and Ecofriendly Approach to Weed Management

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Abstract

Agriculture ecosystems and biodiversity are a global issue of great importance, because the management of unwanted plants like weeds is essential for optimizing agricultural productivity of feeding huge population and maintaining biodiversity. The proliferation of uncontrolled weeds could lead to a significant decline in the global output of crucial crops. Meanwhile, intensive and continuous use of pesticides, herbicides, and/or tillage to control weeds have harmful impacts on both the environment and the long-term productivity of farms. Regarding this matter, transforming weeds into edible vegetables (TWEV) could be an ecologically sound approach to weed management, ensuring sustainable food and nutrition security. This chapter has included pertinent material to raise awareness among different stakeholders about certain overlooked weeds, which have the potential to be a viable source of nutrition for some individuals, such as ivy gourd; tripatri leaves; spiny amaranths; sorrel, haicha, takshak, etc., while others may not recognize their value. The lack of awareness in this area can be addressed by conducting comprehensive research on the recent surge in the popularity of the foraging movement, as well as its historical foundations in food. Simultaneously, it is crucial to acknowledge the delectable and fragrant qualities of numerous weeds, apart from their sustainability benefits. The objective is to utilize the transforming weeds into edible vegetables (TWEV) method to reintroduce the public to the nutritious plants in our surroundings by creating a delicious and visually appealing dish mostly made from weeds. To achieve this, it has become necessary to implement policy changes that encourage consumers to view weeds as edible vegetables for ensuring the future food and nutrition security of humanity in future.

Keywords: functional food, biodiversity, weed management, sustainable agriculture, food safety

1. Introduction

Agrobiodiversity is essential to sustainable agriculture, of which neglected underutilized species (NUS) are key elements. About 30,000 edible plant species have been identified worldwide; of these, more than 7000 crop species have been cultivated for food. Currently, fewer than 150 crop species are commercially cultivated; of these, 103 crops deliver up to 90% of the calories in the human diet, and only four of them (rice, wheat, maize, and potato) provide 60% of the human energy supply. Thus, tens of thousands of edible plant species are relatively "underutilized" and could be used to increase the world's food requirements [1]. Meanwhile, weeds are considered as the undesirable species grown in the field with the mainstream crop. In most cases, these weed species are neglected and removed away by the growers, thereby leading to threaten the conservation of sustainable agriculture biodiversity.

Agriculture faces the dual challenge of feeding the world's growing population while sustaining the ecosystems and biodiversity that support humanity. Weeds and their management are critical to achieving agriculture's potential in both these roles. Uncontrolled weeds could reduce global yields of major crops by around 34% [2], yet when too many weeds are removed from farmed landscapes, major declines in other wildlife follow [3, 4]. Current agricultural systems, particularly in the developed world, are dominated by a paradigm of large-scale, intensive, mechanized farming of a few major crops supported by inputs of mineral fertilizers and chemical crop protection products [5]. These systems rely on the intensive long-term use of herbicides and/or tillage to control weeds, which can have negative impacts on both the environment and long-term farm productivity.

Food diversity includes not only the domesticated plant and animal species, but also the wild animal and plant species. Given the profound changes in agricultural practices and in culinary and nutritional habits, food diversity is globally decreasing. Globalization and modernization have resulted in diet simplification and an increased dependency on a few staple crops for most nutritional needs [6]. Food homogenization relates not only to the consumption of fewer species, but also to intraspecies homogenization. According to Food and Agriculture Organization (FAO) (2004), about 75% of the genetic diversity of agricultural crops was lost during the last century. Many local varieties of crops and animal breeds are threatened by extinction and most wild edible plants are not consumed anymore or only seldom [7, 8].

The decrease of food diversity has led to an increasing concern among researchers, consumers, and farmers about its effects on human health, food security, and food sovereignty [6, 9, 10]. Both scientists and social movements are aware of the need for policies that promote diversified, and environmentally and socially sustainable food production systems [11–13]. Therefore, transforming weed species that are generally considered as underutilized or orphan species into an edible vegetable species could be an alternative option to take part in the food diversification processes. In addition, it would certainly be a sustainable ecofriendly approach of weed management.

In the context of this work, we define edible weed plants as plant species used as sources of food that are neither cultivated nor domesticated but available from their wild natural habitats, including growing in agricultural and disturbed areas. Traditional food systems have typically used a large number of wild edible plants, including weedy relatives of crops. Weeds probably began to contribute substantially to the human diet with the beginning of agriculture, which favored the development of their ecological niches. They were a backup resource in times of shortage, accounting for a significant input of micronutrients and allelochemicals with a prophylactic effect [14]. Nowadays, the consumption of weed edible plants, although often difficult to assess, is still significant at local and global scales [15, 16]. Particularly, ethnobotanical surveys in the Mediterranean region reflect the fact that gathering wild edible plants is at the crossroads of two divergent tendencies such as: (1) a decline in the habit of eating wild edible plants among the general population; and (2) a renewed interest among some young and middle-aged urban classes in the consumption of wild food resources [17, 18].

This chapter presents the status of weed species focusing on their types based on morphology; growth habit, ecology, and economic importance. This article also examines the crop-weed interaction and sustainable weed management options like the cropping pattern; crop rotation; cover crops; and soil health improvement. In addition, this chapter explores the potentiality of the transformation of weeds to vegetables with reference to their nutritional and ethnobotanical importance. This chapter further denotes the future scope of transforming weeds into edible vegetables through the motivational approaches of changing consumers' attitudes to the diversification of foods.

All the information incorporated in this chapter has been collected from the different sources like Internet browsing through Google Chrome, recently published scientific papers, articles, and book chapters. We have used different keywords to facilitate the search of collecting the relevant information like weed; edible vegetables; sustainability; food and nutrition security; world population and climate change; agricultural production, etc. The collected information was compiled and stated in different headings and subheadings for a comprehensive understanding of the topic.

2. Status of weed species

2.1 The occurrence and classification of global weed

The Oxford English Dictionary states that the term "weed" comes from the Anglo-Saxon word "Woed," meaning August [18]. Weeds are undesirable, nonuseful, prolific, tenacious, competitive, dangerous, and even toxic plants that disrupt agricultural operations, increase work, diminish yields, and lower living standards [19]. The global diversity of weed species is a topic of widely varying estimates. According to some studies, there are around 250,000 plant species in nature. Among these, 8000 species are classified as weeds, with around 250 species being particularly prevalent in agricultural and nonagricultural environments [20, 21]. Others have also brought forward a varying number of weed species, such as 3000 by Marwat et al. [22]; 30,000 by Mishra and Gautam [23] and Soni et al. [24] and so on. Despite the conflicts about the number of weed species, there is no argument about their detrimental impact on crop productivity. The economic impact of weeds on humans is often underestimated due to their ubiquity, which leads to insufficient assessment of the losses incurred and the expenditures associated with their management [25]. Negative effects of weeds on ecosystems are substantial; invasive weeds are the second leading cause of biodiversity loss, behind habitat degradation [26]. Weeds are highly variable across their range [27]. When it comes to the taxonomy of weeds, there is no key or identification guide to help you get started. In order to aid the user in identifying a specific weed, most field guides on agricultural weeds categorize weeds according to plant families and highlight characteristics shared by those families [28].

2.2 Weed classification

Weeds are a constantly evolving category, and the word itself is relative [29]. Weed classification facilitates the implementation of weed control strategies that target certain groups of weeds rather than individual ones. In order to categorize weeds, one may look at their life duration, morphology, ecological affinities, habitat and habit, economic significance, specificity, and reproductive mechanism.

2.3 Based on life span

Weeds are categorized into three types based on their life span: annual, biennial, and perennial.

2.3.1 Annual weeds

Annual weeds complete their life cycle within 1 year or one season by emerging from seed, setting seed, and dying in less than 1 year. The majority of this plant's propagation occurs from seeds, and the small plants have delicate stems and short roots [30]. The most common field weeds are summer annuals [26, 31]. Summer annual weeds often appear promptly as soil temperatures rise throughout the spring or early summer. Management of this category of vegetation is frequently challenging due to the fact that numerous species thrive in summer conditions. Examples include *Parthenium*, *Amaranthus* spp.., *Euphorbia* spp., *Digitaria sanguinalis*, *Fallopia japonica*, *Euphorbia maculata*, *Amaranthus retroflexus*, *Chenopodium giganteum*, *Setaria viridis*, and *Salsola tragus*. Monsoon annual weeds emerge during the beginning of the monsoon season and finish their life cycle by the end of the rainy season. Weeds are a major issue during the rainy season because they grow rapidly, compete for resources (light, nutrients, and space), and drastically reduce crop yields and productivity [32]. The most common monsoon weeds include *Commelina benghalensis*, *Boerhavia* erecta, *Celosia cristata*, *Euphorbia hirta*, *Parthenium hysterophorus*, *Cynodon dactylon*, *Cyperus rotundus*, *Dactyloctenium aegyptium*, *Phyllanthus niruri, Amaranthus* spp., etc. Whereas, winter annuals complete their life cycle during the winter season (October/ November to February in the Indian subcontinent). In the mild soil of autumn and early winter, winter annual weed seeds germinate, then mature and bloom early the following year. Upon dispersing their fully developed seeds, they perish. Examples include *Stellaria media*, *Cardamine hirsuta*, *Lamium amplexicaule*, *Lamium purpureum*, *Veronica officinalis*, *Chenopodium album*, *Portulaca oleracea*, *Avena fatua*, *Barbarea vulgaris*, etc. Summer annual weeds reduce agricultural productivity more than winter ones [33].

2.3.2 Biennial weeds

The life cycle of biennial weeds requires a minimum of 2 years or two seasons to be completed. They undergo vegetative development during the first year or season and thereafter produce blooms and seeds in the following year or season. According to several studies, biennial weeds are less common in a given agricultural area than annual or perennial weeds [34, 35]. This may be the result of harvesting them alongside the cereal plants, prior to their ability to produce seed. Uncultivated areas are the most common habitats for them [31]. The important biennial weeds include *Daucus carota*, *Asphodelus* spp., *Launea* spp., *Verbascum thapsus* L., *Carduus nutans* L., *Oenothera biennis*, and *Arctium* spp. [31].

2.3.3 Perennial weeds

Perennial weeds are plants that persist and thrive for a duration beyond two or more years, with a storage organ to support their growth. They have other means of proliferation than seeds, including as rhizomes, stolons, and tubers. Because of this process, mechanical weeding, which is used to control annual weeds, does not work on perennial weeds [36]. Throughout their life span, perennial weeds undergo many cycles of blooming and fertilization [30]. Dependent on the propagule structure, perennial weeds may be further classified. Simple perennials reproduce mostly via seed. For instance, *Lantana camara*, *Acacia* spp., *Ziziphus* spp., and *Sonchus arvensis*. While bulbous perennials propagate by underground parts like bulbs, rhizomes, tubers as well as seeds. Some examples of bulbous perennials include *Pan kanis*,*Typha* spp., *Cyperus rotundus*, *Allium* sp., and *Sorghum halepense*. Creeping perennials are another kind of perennial weeds that may spread by seed or by the lateral growth of their aboveground stems or roots. Some examples of this group are *Cynodon dactylon*, *Oxalis litifolia*, *Cirsium arvense*, *Elytrigia repens*, and *Convolvulus arvensis*. The term "shallow-rooted perennial weed" describes a kind of perennial weed that has a root system that is just 20 to 30 cm deep. For instance, *Cynodon dactylon* and *Agropyron repens*. In contrast, the roots of deep-rooted perennial weeds reach 1 meter or more. Examples include *Cyperus rotundus*, *Sorghum halepense, Acacia* spp., and *Ziziphus mauritiana*.

2.3.4 Ephemeral weeds

Epiphytes are the common name for annual weeds that do not last long. The life cycle of this plant is just 2 to 4 weeks long. Such weeds include *Phyllanthus niruri*, *Cardamine hirsuta*, and *Stellaria media*.

2.4 Based on ecological affinities

Weeds are grouped according to their ecological preferences: wetland, garden land, and dryland weeds.

2.4.1 Wetland weeds

The term "wetland" broadly spans various types of water bodies, including seagrass meadows, coastal marshes, forested wetlands, inland freshwater, and saline wetlands. This plant is semiaquatic in nature. Most wetland weeds grow in anaerobic conditions. They are capable of thriving in two distinct ecological conditions: dehydration and moderate aridity. Most of the weeds in wetland agriculture conditions are annuals, but perennials may be found on the bunds and channels. Some of them possess floating mechanisms in stem or leaves [37]. They are disseminated by seed. E. g. *Echinochloa crus-gulli*, *Panicum* spp., *Eclipta prostrata*, *Ammannia baccifera*, *Eclipta alba*, *Azolla pinnata*, *Ceratophyllum demersum*, *Cyperus* spp., *Damasonium alisma*, *Lemnaceae*, *Eleocharis palustris*, and *Epilobium hirsutum*.

2.4.2 Garden land weeds

Weeds that are found under irrigated conditions in the garden lands are called garden land weeds [24]. They are intermediate between dry land and wetland weeds concerning their water requirement. They require more soil moisture but do not normally tolerate water-logged situations. E.g. *Digitaria* spp.,*Trianthema portulacastrum*, *Portulaca oleracea*, *Amaranthus* spp., *Chenopodium album*,*Taraxacum officinale*, and *Elytrigia repens*.

2.4.3 Dryland weeds

The drylands in different parts of the globe vary from 20 to 95%, with around 45% of the world's geographical area being dryland [38]. In drylands, weeds may reduce output by 10–98% or cause crop failure [38]. Due to the scarcity of all necessary crop production components in arid regions, weeds and crop plants engage in fierce struggle [39]. Early life cycle completion, deep root system, modified leaves, decreased leaf area, waxy leaves, lower transpiration rate, and copious seed production allow weeds to thrive in unfavorable agroclimatic conditions [39]. The majority of the weeds in the dryland regions are perennials; a smaller portion are annuals and biennials [40]. E.g. *Tribulus terrestris*, *Argemone mexicana, Andropogan contortus, Perotis indica, Dactyloctenium aegyptium, Cynodon dactylon, Panicum repens, Abutilon indicum, Acanthospermum hispidum, Achyranthes aspera, Aerva lanata, Amaranthus spinosus, Aristolochia bracteata, Borreria hispida, Cleome viscosa, Leucas aspera,Tephrosia spinosa*, and *Solanum elaeagnifolium*.

2.5 Based on the place of occurrence

Based on where they live, weeds are divided into a number of groups, such as weeds in playgrounds, deserts, pastures, forests, and croplands.

2.5.1 Crop land weeds

Crop land weeds are weeds that grow mainly among crops. The majority of weeds infest the cultivated lands and obstruct the farmers from successful crop production. For instance, *Chenopodium album*, *Echinochloa* spp., *Phalaris minor*.

2.5.2 Weeds of pasture lands

Weeds found in pasture or grazing grounds. Pastures represent about half of the global agricultural area where productivity losses from weeds are significant. Weeds negatively interfere with the structure of the forage canopy and the grazing habits of animals. Some common pasture land weeds include *Indigofera tinctoria*, *Oxalis enneaphylla*, *Parthenium hysterophorus,* and *Cleome viscosa*.

2.5.3 Weeds of wasteland and roadsides

The roadside and wasteland areas are incredibly important to conserve species biodiversity. In addition to endangering biodiversity, heavy weed infestations in certain places can intensify bushfires. Roadsides are vectors of spread for invasive and other nonnative plants. Therefore, fields located along roadsides could harbor more weeds and fewer native species compared to isolated fields [41]. Weeds in waste areas and along roadsides should be controlled because these areas provide ideal conditions for the spread of invasive species and weed seeds [42]. Some dangerous roadside weeds include *Cirsium arvense, Carduus nutans, Cirsium vulgare, Dipsacus fullonum* L., *Conium maculatum, Lythrum salicaria, Euphorbia esula, Pastinaca sativa*, etc.

2.5.4 Weeds of forest land

Plant species that interfere with other plants' ability to germinate and grow in the forest are known as forest weeds. There are two types of forest weeds: those that thrive in nursery settings and those that thrive in more established forest settings like plantations and stands. The weeds in forest nurseries have a striking resemblance to those in farmed crops. They are mostly annual and perennial herbaceous weedy species. However, forest plantations and forest stand weeds include ferns, herbaceous annual and perennial weeds, woody weeds, such as shrubs, bushes, and shoots from the stumps of different tree types [43]. Some common examples are *Ambrosia artemisiifolia, Amorpha fruticosa, Asclepias syriaca, Erigeron canadensis, Solidago gigantea, Sorghum halepense, Sambucus nigra, Stenactis annua, Pteridium aquilinum, Rubus caesius*, etc.

2.5.5 Weeds of playgrounds

A large number of annual and perennial weeds are found in playgrounds and deprive the natural beauty. They are usually hardy, prostrate perennials, capable of withstanding any amount of trampling. Some common examples are *Alternanthera echinata, Tribulus terrestris, Eleusine indica* (L.), *Ambrosia artemisiifolia* L., etc.

2.6 Based on morphology

Scientists studying weeds most often use this categorization. Weeds are categorized according to their morphology as grass, sedge, or broad-leaf weed.

2.6.1 Grass weeds

All plants belonging to the Poaceae family are often referred to as grasses, known for their distinctive long and slender leaves with pointed edges. They possess elongated, slender leaves with veins that run parallel to one another. The plants possess tubular, cylindrical stems known as culms, which often include nodes [23, 24]. *Echinocloa colonum, Cynodon dactylon, Avena fatua* L., *Avena sterilis* L., *Digitaria sanguinalis* L., *Echinochloa crus-galli* (L.), *Poa annua* L., *Lolium perenne* L., *Lolium multiflorum* Lam., *Lolium perenne* L., and *Phalaris minor* Retz.

2.6.2 Sedge weeds

The weeds belonging to the Cyperaceae family come under this group. The leaves are mostly from the base having modified stems with or without tubers. The stem is angular and sturdy, without ligules, with leaves arranged in whorls around it. They are different from grasses, in that their stems are solid, triangular, and have no nodes. Over 2000 species have been confirmed, out of over 5500 that have been described [44]. Sedges are prevalent in tropical Asia and South America, although they do not help agriculture or productivity. However, they may be used as soil binder, medication, feed, and raw materials for small enterprises [44]. Some common examples are *Cyperus esculentus, Cyperus rotundus, Cyperus difformis* L., *Cyperus iria* L., *Fimbristylis miliacea, Scirpus Tourn.* ex L., *Sumatroscirpus Oteng-Yeb., Protocyperus, Trachystylis S.T. B., Eleocharis melanocarpa Torr.,* and *Eleocharis microcarpa Torr.*

2.6.3 Broad-leaved weeds

Identifying broad-leaved weeds is often straightforward. They distinguish themselves from grasses by their distinct shape and function. Commonly known as dicots, broad-leaved weeds possess big, flat leaflets with veins that radiate in several directions. They can vary significantly in appearance, with diverse leaf shapes and flower structures [24]. The physiological difference allows for the use of selective weed control methods to control broadleaf weeds without injury to the desirable grasses and inhabitants like earthworms. Some of the popular broadleaf weeds are *Parthenium hysterophorus, Amaranthus viridis, Chenopodium album, Flaveria australasica, Digera arvensis, Tridax procumbens, Chara zeylanica,* and *Nitella hyalina*.

2.7 Based on specificity

A few other weeds deserve special attention due to their specificity. They are poisonous weeds, parasitic weeds, and aquatic weeds.

2.7.1 Poisonous weeds

Poisonous weeds inflict illness and death on cattle, leading to significant financial losses. These weeds are harvested along with fodder or grass and fed to cattle or while grazing the cattle consume these poisonous plants. For instance, *Datura fastuosa*, *Datura stramonium,* and *Datura metel* are poisonous to animals and human beings. The berries of *Withania somnifera* and seeds of *Abrus precatorius* are poisonous. *Lochnera pusilla* is poisonous to cattle and *Solanum nigrum* poisonous to children on rare occasions.

2.7.2 Parasitic weeds

The parasitic weeds are particularly noxious since they directly extract valuable water and nutrients from the host plant [45]. The unique root like haustorium of a parasitic weed penetrates the host plant's vascular system and allows the parasite to assimilate nutrients and water [46]. The parasite weeds are either total parasite (the weeds that depend completely on the host plant) or partial parasites (the weeds that partially depend on the host plant for minerals and capable of preparing their food from the green leaves are called as partial parasites). *Orobanche* spp., *Striga* spp., *and Cuscuta* spp. are the most common parasitic agricultural weeds with economic importance in many parts of the world [47]. Some other examples include *Dendrophthoe falcata, Orobanche uniflora, Orobanche aegyptiaca, Orobanche cernua, Orobanche crenata, Orobanche cumana, Orobanche foetida, Orobanche minor, Viscum* spp., *Santalum* spp., *Aeginetia indica, Lathraea squamaria, Cistanche, Cuscuta, ramose, Striga hermonthica, Striga asiatica*, and *Striga gesnerioides.*

2.7.3 Aquatic weeds

Unwanted plants, which grow in water and complete at least a part of their life cycle in water, are called as aquatic weeds. They are further grouped into four categories as submersed (These weeds are mostly vascular plants that produce all or most of their vegetative growth beneath the water surface), emersed (These plants are rooted in the bottom mud, with aerial stems and leaves at or above the water surface), marginal (Most of these plants are emerged weeds that can grow in moist shoreline areas with a depth of 60 to 90 cm water), and floating weeds (These weeds have leaves that float on the water surface, either singly or in cluster). Examples include; *Eichhornea crassipes, Pistia stratiotes, Salvinia molesta, Nymphaea pubescens, Typha, Polygonum, Alternanthera, Ipomea, Nelumbium speciosum, Jussiaea repens, Utricularia stellaris, Ceratophyllum demersum*, etc.

2.8 Based on economic importance

2.8.1 Absolute weeds

Weeds that have no economic value and grow out of their proper place are called absolute weeds. *Euphorbia hirta*, *Cyprus rotundus*, *Amaranthus spinosus*, *Anagallis arvensis*, etc., are some of the important absolute weeds.

2.8.2 Relative weeds

Weeds that have some economic importance but are called weeds because these are growing out of their proper place. S*accharum munja* and *Typha latifolia* are used in the cottage industry and *Phalaris, Avena ludoviciana, Cynodon dactylon*, etc., can be used as fodders. A crop plant in another crop field, which is not desirous, is also referred to as relative weed. For instance, cotton in maize.

2.9 Based on origin

Based on origin, weeds are classified as indigenous and exotic weeds.

2.9.1 Indigenous weeds

All the native weeds of the country are coming under this group and most of the weeds are indigenous. E.g. *Acalypha indica* and *Abutilon indicum*.

2.9.2 Exotic weeds

These are the weeds introduced from other countries. These weeds are normally troublesome and their control becomes difficult. E.g. *Parthenium hysterophorus, Phalaris minor,* and *Acanthospermum hispidum.*

2.10 Based on association

When two plants are living together, it is called association. Based on the association, they are either season bound weeds or crop bound weeds.

2.10.1 Crop bound weeds

Weeds that usually parasite the host crop partially or fully for their nourishment i.e., parasitism are also called parasitic weeds. Those parasites that attack roots are termed root parasites and those parasites that attack the shoot of other plants are called stem parasites.

2.10.2 Season bound weeds

Season bound weeds are seen in that particular season, irrespective of crop. These are either summer annuals or winter annuals. *Sorghum halepense* (perennial) is a summer perennial and *Cirsium arvense* is winter perennial. *Phalaris minor* and *Avena fatua* are winter season annuals.

3. Crop-weed interaction

Crop-weed interactions refer to the relationships between cultivated crops and the unwanted plants (weeds) that grow alongside them. These interactions can have significant impacts on crop growth, yield, and overall agricultural productivity. There are various types of interactions that can occur between crops and weeds, including competition for resources, such as water, nutrients, and sunlight, allelopathy (chemical interactions between plants), and facilitation (where weeds can provide benefits to crops under certain conditions).

3.1 Competition for resources

Weeds compete with crops for essential resources like water, nutrients, and sunlight, which can reduce crop growth and yield. This competition can be particularly severe in densely populated weed communities or under conditions of limited resources. For example, a review by Mohler [48] highlights the competitive interactions between crops and weeds, emphasizing the importance of resource availability and weed density in determining the outcome of competition. Dukes et al. [49] also highlighted the significance of resource competition in shaping plant community structure and agricultural productivity.

3.2 Allelopathy

Some weeds release chemicals into the soil that inhibit the growth of nearby crops, a phenomenon known as allelopathy. These chemicals can hinder germination, root development, and overall crop performance. For instance, Qasem and Foy [50] demonstrated the allelopathic potential of certain weed species on crop germination and seedling growth, indicating the significance of chemical interference in crop-weed interactions. Research by Rice [51] and Willis and Rice [52] demonstrated the allelopathic effects of certain weed species on crop germination and growth.

3.3 Facilitation

In some cases, weeds can actually provide benefits to crops. For example, certain weed species may improve soil structure, increase soil organic matter, or attract beneficial insects that help control pests. For instance, a study by Mohler and Callaway [53] showed that certain weed species improved soil conditions and enhanced crop performance.

Weeds that infest the crops have diverged hosts, including insects (**Table 1**), pathogens (**Table 2**), and diseases (**Table 3**).

Name of weed	**Insect host**	**Associated crops**	**Reference**
Cleome sp.	Bollworm	Cotton	[54]
Malvaceous shrubs	Earias spp.	Cotton	[54]
Xanthium indicum	Cutworm	Sugarcane, jute, maize	[55]
Cyperus rotundus			
Cynodon dactylon	Wire beetle	Sugarcane, jute, wheat, lentil	[55]
Eleusine indica			
Echinochloa colona	Short-horned grasshopper, long-horned grasshopper, jute hairy caterpillar	Rice, jute, wheat	[55]
Leersia hexandra			
Cyperus rotundus	Green leafhopper, brown plant hopper, stem borer	Rice, sugarcane	[55]
Echinochloa colona			
Paspalum scrobiculatum			
Solanum torvum	Aphid, mite, thrips, fruit borer	Mustard, chili, mustard	[55]
Physalis heterophylla			
Cynodon dactylon	Fall armyworm	Maize	[55]
Cyperus rotundus			
Chenopodium album L.	Whitefly	Rice, wheat	[55]
Cynodon dactylon			
Dactyloctenium aegyptium			

Table 1.
Weeds-crop interaction in response to the inset host.

Name of weeds	**Plant pathogen host**	**Associated crops**	**Reference**
Acanthospermum hispidum	*Meloidogyne javanica*	Soybeans, sugarcane, peanuts, cotton	[54]
Ageratum conyzoides	*Meloidogyne javanica*, *Verticillium dahliae*	Rice, maize, wheat	[54]
Amaranthus hybridus	*Pratylenchus zeae*, *M. javanica*	Soybeans, cotton	[54]
Amaranthus spinosus	*Rotylenchulus reniformis*	Rice, sorghum, cowpea, maize	[54]
Chenopodium murale	*M. incognita*	Maize, wheat, soybean	[54]
Commelina benghalensis	*Pratylenchus zeae*	Chili, barley, tea, groundnut	[54]

Name of weeds	Plant pathogen host	Associated crops	Reference
Commelina diffusa	*R. reniformis*	Soybean, rice, maize, wheat	[54]
Cynodon dactylon	*Sporisorium sorghi*	Rice, wheat, maize, cotton	[54]
Nicandra physalodes	*M. javanica*	Rice, soybean, cotton, onion, tomato	[54]

Table 2.
Weeds-crop interaction in response to the plant pathogen host.

Name of weeds	Disease host	Associated crops	Reference
Echinochloa colona	Sheath rot, stem rot, sheath blight, blast	Rice, wheat, sugarcane	[55]
Cyperus rotundus			
Alternanthera sessilis	Stem rot, blight, leaf spot, rust	Sugarcane, rice, wheat	[55]
Amaranthus viridis L.			
Amaranthus spinosus L.			
Chenopodium album L.			
Croton bonplandianus Baill.	Anthracnose	Mustard, lentil, chili	[55]
Brassica kaber (DC.) L.C. Wheeler	Alternaria blight	Mustard, lentil, chili	[55]
Solanum nigrum	Pepper veinal mottle virus	Pepper	[54]
Tridax procumbens	Groundnut streak necrosis		[54]

Table 3.
Weeds-crop interaction in response to the disease host.

4. Sustainable management approach of weeds

4.1 Cropping pattern

Cropping patterns are defined as the percentage of land that is farmed for various crops at different times of the year [56]. For a specific land area, cropping pattern delineates the crop's timing and arrangement. It is impossible for farmers to cultivate crops in every season of the year throughout the nation. In certain Asian nations, there are three distinct seasons: rabi (October to March), kharif-1 (April to June), and kharif-2 (July to September). These are referred to as the upland rice, rainfed rice, and irrigated rice seasons in the context of rice cultivation [56].

Irrigated rice-fallow-rainfed rice, barley-fallow-fallow, irrigated rice-fallow-fallow, irrigated rice-fallow-rainfed rice, fallow-fallow-rainfed rice, fallow-upland rice-rainfed rice, wheat-fallow-rainfed rice, and mungbean-fallow-rainfed rice are regarded as the common cropping patterns in some countries [56]. A fallow time is when there is not any cover of live plants. Repeated fallow periods eventually encourage weed growth and reduce the organic content in the soil. Growing beneficial weeds to reduce fallow may boost soil health and cropping intensity. In this case, the weed infestation can shift to a beneficial or edible weed introduction, replacing the fallow area.

Certain weeds have shorter life cycles than crops, occurring and finishing three or four life cycles prior to the crops blossoming, such as *Parthenium hysterophorus* L., *Achyranthes aspera* L., and *Bidens pilosa* L., which are used for medicinal purpose [57]. Short-lived Kharif and rabi weeds could be the best option for fallow land, such as in kharif season *Parthenium hysterophorus* (organic fertilizer, allelopathic activity); *Amaranthus* spp., *Chenopodium giganteum* (food use); *Cynodon dactylon* (soil erosion control, forage); *Commelina benghalensis*, *Phyllanthus niruri* (medicinal use), etc., are the best options to fit in fallow period. In rabi season, *Stellaria media, Lamium amplexicaule* L., and *Lamium purpureum* L. (cover crop), *Chenopodium album, Cardamine hirsuta* (food use); *Portulaca oleracea* (medicinal, cover crop) weeds could be introduced in fallow period.

Some studies have shown that the fallow-wheat cropping strategy benefited weed species with broad, grassy leaves [58, 59]. *Parthenium hysterophorus, Amaranthus viridis, Chenopodium album, Flaveria australasica, Digera arvensis, Chara zeylanica*, etc., are few common broadleaf weeds that can be used for food and medicine.

4.2 Weeds as cover crop

Cover crops, which are grown on unproductive ground to provide various ecological benefits, can be filled by weeds [60, 61]. While cover crops are not commonly utilized for cash crops, certain species may be harvested for forage or grazed by livestock. Increased soil organic matter, optimized nutrient management, soil conservation, and provision of a host for insects and pests are the most frequently desired benefits of cover crops [62].

Wortman [63] estimated that weeds functioning as cover crops in fallow fields could reduce overwinter nitrogen leaching losses by up to 60% when compared to a barren fallow; thus, they perform a function comparable to that of brassica or grass cover crops that scavenge nitrogen. The utilization of weedy species as cover crops in maize (*Zea mays* L.) and soya beans (*Glycine max* (L.) Merr.), namely common couch (*Elytrigia repens* L.) and common chickweed (*Stellaria media* L.), respectively, has been found to reduce soil erosion and function as an alternative management strategy in comparison to the practice of leaving the ground bare in these crops [62]. *Cynodon dactylon* facilitates erosion control and maintains the stability of dunes.

Lamium amplexicaule L. and *Lamium purpureum* L., when utilized as cover crops in soybean fields, have the potential to serve as hosts for the soybean cyst nematode [64]. *Mimosa pudica* can be utilized as a cover crop of pepper and tomato plants. *Portulaca oleracea* and *Trifolium repens* function as a ground cover. As a ground cover, common grass can operate even in nitrogenous soils. Other ground cover species include *Amaranthus spinosus* L., *Amaranthus viridis* L., *Enhydra fluctuans*, *Oxalis corniculata*, and *Marsilea quadrifolia* L., which were utilized as forage in animal husbandry. *Eichhornia crassipes* and *Leersia hexandra* Sw. were used as mulching materials, they may serve as an effective ground cover [65].

Specific vegetation species, such as field pennycress (*Thlaspi arvense*), are undergoing breeding to develop cover crops with advantageous phenological and agronomic characteristics. These cover crops can also be harvested as oil seed crops for increased economic yield as the seed can be used as a source of biofuel [62].

4.3 Intercropping weeds

The proliferation of weeds can be induced by the combination of extensive row spacing and a substantial population of agricultural plants within each row. Due to their distribution across different altitudes within the same region, numerous weeds can thrive when intercropped with other plants in the same area. *Trifolium repens*, similar to other legumes, serves as a habitat for microbes that fix nitrogen within the soil. As an intercrop, it is compatible with brassicas including broccoli and cabbage.

Certain weed species possess the ability to penetrate deeply enough to gain access to nutrients that agricultural plants are unable to. Weeds facilitate the uptake of these nutrients when the host plant generates new stems or establishes superficial roots. The nutrients are discharged into the upper strata of the soil as a result of the decomposition and mortality of vegetation. In order to break up tough substances, *Taraxacum officinale* possesses robust tap roots that penetrate deeply into the soil. By extracting nutrients from deeper soil that are inaccessible to adjacent shallow-rooted plants, this mechanism aids neighboring plants with weaker roots. Through their roots, they will additionally discharge nitrogen and minerals. As an intercrop, it may be planted in conjunction with any other horticultural species.

Daucus carota serves as a nurse plant for adjacent crops, including lettuce, by offering resistance to excessive sunlight and elevating air humidity. Wasps that seek prey and flies that consume vegetable pests are attracted to it. It exerts a beneficial, empirically supported impact on adjacent tomato plants. When immature, the degree of similarity between this plant and the domesticated carrot is indicated by its edible root. *Daucus carota* may therefore be utilized as an intercrop alongside lettuce, tomato, and carrot.

Weeds are the primary attraction for a multitude of insects that rely on vegetation. To illustrate, the proximity of *Vigna unguiculata* plants to cotton fields serves as a protective barrier against ladybird beetles, which are parasitic insects. Hairy nightshade (*Solanum sarrachoides* Sendtner), as opposed to potatoes' production, serves as the preferred host of the Colorado potato beetle (*Leptinotarsa decemlineata* Say). The presence of *Solanum sarrachoides* reduces the frequency of egg hatching on potatoes. The greatest choice for an intercrop weed in a potato field is the *Solanum sarrachoides* [66].

4.4 Natural repellent-insect host plant

The idea that eradicating weed communities in tropical areas could lead to an increase in agricultural losses caused by insect pests and diseases was first brought up by Wolcott, 1928. Several studies have decisively demonstrated that weedy crops have fewer insect pests than weed-free crops. According to a Nigerian study, cowpea fields infested with weeds like *Syndrella hybidum*, *Eleusine indica*, and *Amaranthus hybridus* had lower populations of *Altica chalybea*, *Ootheca mutabilis*, leafhoppers, and *Empoasca dolichi* than weed-free cowpea plots. The weedy plot generated a higher yield than the weed-free plot [67]. Diehl et al. [68] noted that weedy organic wheat (*Triticum aestivum* L.) fields maintained a larger number and diversity of ground beetles (Coleoptera: Carabidae), many of which are significant predators of insect pests and weed seeds, in comparison to weed-free fields [62].

Weeds can also serve as a natural repellant [54]. Numerous insects and pests are repelled by the scent of the *Datura stramonium* plant. Kumral et al. [69] found that when tested on adult two-spotted spider mites (*Tetranychus urticae*), ethanol extracts made from the leaf and seed of *Datura stramonium* exhibit notable acaricidal, repellent, and oviposition preventive activities [70]. Nectar/apple of Peru, *Nicandra physalodes*, is a type of herb. This plant is alternatively referred to as the "shoo fly plant," owing to the significant insect repellent properties attributed to its principal active chemical constituent, nicandrenone [71]. According to Sahrawat et al. [72], jimsonweed (*Datura stramonium*) can offer a certain degree of efficacy in controlling bacterial blight (*Xanthomonas campestris* pv. malvacearum) and Alternaria leaf spot (*Alternaria macrospora*) on cotton [72].

Weeds serve as alternative hosts for numerous pest organisms (including plant pathogens, insects, mites, nematodes, and rodents) by providing them with food, shelter, and reproductive sites [73]. The weeds that serve as hosts for detrimental insects and disease pathogens are enumerated in **Table 1**.

4.5 Cropping intensity

Some weeds can complete their life cycle within 2–4 weeks. Those weeds could be cultivated in between the short fallow period of two cropping seasons (Rabi-kharif). This cultivation practice would increase the cropping intensity for specific areas. Ephemeral weeds, like *Phyllanthus niruri*, which offer medicinal properties, are short-lived annuals that finish their life cycle in 2–4 weeks. Edible weeds, *Cichorium intybus* (chicory) [74] and *Coronopus didymus* (swinecress) [75], need a cool, damp, and shaded microclimate to grow and develop, which lucerne and berseem crops provide. Roadside patches and wasteland are suitable habitats for *Bidens pilosa*, *Amaranthus* spp., and *Corchorus* spp., all of which have higher protein, calcium, and iron contents than spinach [72]. Cultivating these kinds of species in the nonproductive shady areas or under multistoried plants will increase agricultural productivity and crop intensity for the certain area.

Weeds can be utilized in mixed cropping systems, which offer benefits in terms of enhanced food production. Altieri and Liebman [76] recommended that in multiple crop farming systems, weeds, including *Sonchus asper*, *Chenopodium album*, *Amaranthus* spp., and *Galinsoga parviflora*, could be encouraged to be grown. Grain that is collected is used as food in the Sahara and sub-Saharan regions from a variety of wild grasses, such as *Eragrostis* spp. In arid regions, this weed might be a superior choice for increasing cropping intensity. Two varieties of wild rice, called *Oryza barthii* and *Oryza longistaminata*, are harvested from marshy areas when rice harvests are low [54]. In bare terrain, those species could be used to increase cropping intensity.

4.6 Soil health improvement/nitrogen (N2)-fixation/legume weed species

Weeds may serve as significant agents in soil conservation. Weed roots have the capacity to provide channels for the passage of air and water in the soil and stabilize erodible soil. By emitting volatile compounds and antibiotics such as phenazine, rhizobacteria in the roots of weeds stimulate plant growth. The determination of the microbial biomass in the rhizosphere is determined upon the composition of plant efflux, which exhibits species-specific characteristics. The proportion of microbes found in the root zone differed depending on the specific weed species. For instance, *Bacillus sphaericus* was detected in 19.4% of the roots of *Echinochloa crus-galli*, *Pseudomonas chlororaphis* was found in 12.9% of the roots of *Spergula arvensis*, *Stenotrophomonas maltophilia* was observed in 17.5% of the roots of *Solidago canadensis*, *Variovorax paradoxus* was found in 7.5% of the roots of *Lolium multiflorum*, *Arthrobacter ilicis* was detected in 6.3% of the roots of *Chenopodium album* [31]. Therefore, the presence of weed community will alter the variety and quantity of beneficial or harmful microorganism. Wortman et al., 2013 reported early season arable weed communities *Chenopodium album* L., *Abutilon theophrasti* Medik., *Amaranthus retroflexus* L., *Thlaspi arvense* L. and *Setaria viridis* (L.) P. Beauv. were found to have a significant negative impact on arbuscular mycorrhizal fungi [62].

Weeds have the potential to serve as a soil organic matter source by extracting nutrients, moisture, and light, which are essential for the production of carbohydrates. Vidya et al. [77] documented that fresh *Eichhornia crassipes* plants consist of 95.5% moisture by weight, in addition to 0.04% nitrogen, 0.06% phosphorus, 0.20% potassium, and 3.5% organic matter. Biradar & Patil, 2001 produced vermicompost by utilizing vegetation that is rich in organic matter, namely *Parthenium hysterophorus*, *Cassia sericea*, *Achyranthes aspera*, and *Euphorbia geniculata*.

The recycling of weed biomass contributes to the soil's nutrient content. The leaves, stems, roots, and bulbs of *Chromolaena odorata* are primarily nutrient-dense. Maximum nitrogen fixation was observed in weedy grasses, such as *Brachiaria humidicola*, *Paspalum notatum*, and *Panicum maximum*, which obtain as much as 40% of their nitrogen needs via fixation [78]. *Leptochloa fusca* has shown high nitrogen fixation activity [79]. These weeds can be grown in the fallow season to improve soil health to get better crop in the later season.

Anabaena azollae is frequently regarded as a disruptive shrub due to its expeditious establishment on aquatic surfaces. It is a free-floating aquatic fern renowned for its bioremediation potential, short doubling time, and nitrogen-fixing capability [80]. The rate at which nitrogen is fixed by *Anabaena azollae* Strasburger can reach 1.1 t/ha-year, which is considerably greater than the nitrogen fixation rate observed in legumes (0.4 t N/ha-year) [81].

5. Transformation of weeds to vegetables

Based on the information provided, it has been discovered that weeds do not belong to a distinct category of plants, but rather are differentiated according to their requirements by customers. If individuals were to regard weeds as a crucial food source, the adoption and cultivation of them alongside the existing mainstream agricultural products would become more feasible. Therefore, using this method would be an effective way to ensure the efficient use of land resources in several developed and developing countries worldwide. Furthermore, customers are anticipated to be motivated to alter their perspective regarding certain nourishing and delectable wild plants that are abundantly present in their surroundings (**Table 4**).

However, the utilization patterns of weed plant species are typically not fixed and are mostly associated with either a sudden or a gradual decline in traditional knowledge and behaviors. The variations in weed plant utilization patterns vary geographically and are linked to shifts in lifestyle, urban development, extensive agricultural practices, less exposure to natural environments, and numerous other factors. Furthermore, periods of starvation appear to be a thing of the past for economically advanced nations. Food derived from developed crops and purchased from the supermarket is easily accessible and requires minimal work, whereas gathering wild species is a more time-consuming process that is reliant on the season. However, the significance of weeds and wild plant species in ensuring food security and influencing

English name	Scientific name	Family	Useful part	References
Ivy gourd	*Coccinia grandis*	Cucurbitaceae	Fruit	[82]
Tripatri leaves	*Desmodium triflorum*	Leguminosae	Leaf	[82]
Spiny amaranth	*Amaranthus spinosus*	Amaranthaceae	Leaf, stem	[82]
Leaf amaranth	*Amaranthus viridis*	Amaranthaceae	Leaf, stem	[82]
Haicha	*Alternanthera sessilis*	Amaranthaceae	Leaf, stem	[82]
Goosefoot	*Chenopodium album*	Chenopodiaceae	Leaf, stem	[82]
Marsh herb	*Enhydra fluctuans*	Compositae	Leaf, stem	[82]
Indian pennywort	*Centella asiatica*	Umbelliferae	Leaf	[82]
Sorrel	*Rumex vesicarius*	Polygonaceae	Leaf	[82]
Alligator weed	*Jussiaea repens*	Onagraceae	Leaf	[82]
Creeping wood sorrel	*Oxalis corniculata*	Oxalidaceae	Leaf	[82]
Garden purslane	*Portulaca oleracea*	Portulacaceae	Leaf	[82]
Lafa	*Malva verticillata*	Malvaceae	Leaf	[82]
Fern	*Dryopteris filix-mas*	Polypodiaceae	Leaf	[82]
Watercress	*Nasturtium officinale*	Brassicaceae	Leaf	[82]
Roselle	*Hibischus sabdariffa*	Malvaceae	Leaf, stem, flower, fruits, seeds	[83]
Marsh Barbel	*Hygrophila auriculata*	Acanthaceae	Leaf, root	[83]
Horse purslane	*Trianthema portulacastrum*	Aizoaceae	Root, leaf, stem	[83]
Indian turnsole	*Heliotropium indicum*	Boraginaceae	Leaf	[83]
Black nightshade	*Solanum nigrum*	Solanaceae	Immature fruits, leaf	[84]
Balloon vine	Cardiospermum halicacabum	Sapindaceae		[85]
Bengal Shrub-mint	*Pogostemon benghalensis*	Lamiaceae	All parts	[86]
Skunkvine	Paederia foetida	Rubiaceae	All parts	[87]

Table 4.
List of weeds with the edible parts.

alternative consumption patterns is underscored by the conversion of weeds into edible vegetables. Food plants that are commonly associated with weed status should not be solely categorized as "famine food." In fact, many of these plants are utilized as vegetables in many nations due to their high nutritional content, which often surpasses that of mainstream vegetable crops (as shown in the **Tables 5–8**). Furthermore, it should be noted that not all traditions have disappeared. In certain regions, for various reasons, ancient customs are still practiced, while in other areas, they have been abandoned.

In light of the declining quality of retail goods, the use of pesticides to eliminate weeds, which has negative effects on the environment and human health, has

Name	Ethnobotanical use	Reported pharmacological activity	References
Dheki (*Dryopteris filix-mas*)	Cough Asthma Phthisis Fever Dyspepsia Stomachache Diarrhea Insect and pest repellant Hemoptysis Constipation	Antioxidant Cytotoxic Antimicrobial CNS stimulant	[83]
Hatisur (*Heliotropium indicum*)	Ulcers Sores Wounds Gum boils Stings of insects Rheumatism Gonorrhea Putrefaction Pyoderma Ringworm infection Diuretic Intractable fever Sore throat Eye lotion Whooping cough in children	Antitumor Antimicrobial Anti-inflammatory Wound healing Antiproliferative Antituberculosis Gastroprotective Immunostimulant Antioxidant Antihyperglycemic Antihelminthic	[83]
Takshak (*Hibiscus sabdariffa*)	Diuretic Gastrointestinal disorders Liver diseases Fever Hypercholesterolemia Hypertension Sore throat Cough Stomachic Emollient	Hepatoprotective Antioxidant Anti-obesity Anticholesterol Anticancer Inhibition of the contractility of rat bladder and uterus Antibacterial Antihypertensive Antianemic Antidiabetic Diuretic Anticancer Nephroprotective Antipyretic Anti-inflammatory Analgesic	[83]
Kulekhara (*Hygrophila auriculata*)	Aphrodisiac Diseases of the urinogenital tract Dropsy from chronic Bright's disease Hyperdipsia Flatulence Diarrhea Dysentery Leukorrhea Gonorrhea Asthma Blood diseases Gastric diseases Inflammation Cancer Rheumatism Painful micturition Menorrhagia	Anti-inflammatory Antipyretic Hematopoetic Hepatoprotective Diuretic Antidiabetic anthelmintic Antibacterial Antimotility Antioxidant Aphrodisiac Spermatogenic	[83]

Name	Ethnobotanical use	Reported pharmacological activity	References
Gadabani (*Trianthema portulacastrum*)	Pain Constipation Stomachic Bronchitis Heart diseases Anemia Inflammation Piles Ascites Liver asthma Jaundice Amenorrhea Helminthiasis Dropsy Edema Vermifuge Rheumatism Antidote to alcoholic person Fever Corneal ulcers Itching Dimness of sight	Antifungal Analgesic Antihyperglycemic Hepatoprotective Hypolipidemic Anticarcinogenic Anthelmintic Antioxidant	[83]
Hakuch (*Psoralea corylifolia*)	Psoriasis Vitiligo Eczema Leprosy	Diuretic Laxative Aphrodisiac Antihelminthic Estrogenic Anti-prostrate cancer Spermatorrhea Abdominal distension	[88]
Nunia (*Portulaca oleracea*)	Diarrhea Diabetes Toothache Asthma Dysentery Gastric pain Vermicide Hemorrhoids	Purgative In bleeding piles, gums, constipation Anti-inflammatory Diuretic Muscle relaxant Osteoporosis Psoriasis Antiulcerogenic	[89]
Lata Mouri (*Digera muricata*)	Constipation Diabetes Kidney stone Laxative	Hepatoprotective Antimicrobial Antidiabetic Anthelmintic Antitesticular toxicity Nephroprotective	[90]
Tit begun	Rheumatism and gouty joints Skin diseases Tuberculosis Nausea Nervous disorders Cough Diarrhea Inflammations	Anticancerous Anti-stress effect Antiallergic Estrogenic activity Hepatoprotective Anticonvulsant Antidiabetic Immunostimulant Cardioprotective Analgesic Cytotoxic activity Antiseizure activity	[84]

Name	Ethnobotanical use	Reported pharmacological activity	References
Jui lota	Intestinal disorder Intermittent fever Antidote to snakebite Cough and cold Hemorrhage Malaria Pneumonia Tuberculosis Scabies Ringworms Diarrhea, dysentery, and indigestion Lactation	Antimicrobial Larvicidal against *Aedes* sp. Anticancerous	[86]
Gandhavadulia	Rheumatism Urinary retention and for urinary bladder stones Flatulence Toothaches Piles Asthma Diarrhea	Antinociceptive Anti-inflammatory Antitumor Anti-hyperuricemic Antitussive Analgesic	[87]
Futka	Rheumatism Abdominal pain Orchitis Dropsy Lumbago Skin diseases Cough Nervous disorders Hyperthermia	Anti-inflammatory Anti-arthritic Antidiabetic Anxiolytic activity Antiulcer Apoptotic activity Antibacterial Antiviral Antidiarrheal Hepatoprotective Nephroprotective	[85]

Table 5.
List of weeds with their ethnobotanical uses in response to specific pharmacological constituents.

prompted a reevaluation of weed control strategies. One alternative strategy is to turn weeds into edible vegetables.

6. Future prospects of transforming weeds into edible vegetables (TWEV)

The utilization of herbicides for weed control presents numerous benefits and drawbacks that have been extensively studied. However, the alternative method of weed management known as transforming weeds into edible vegetables (TWEV), which is a sustainable ecological strategy, has not yet received scientific scrutiny. According to the Oxford Dictionary, a weed is defined as a “wild plant that grows in places where it is not desired and competes with cultivated plants.” Within the context of this study, weeds are defined as foliate vegetation that spontaneously proliferates within or around the periphery of cultivated areas, without deliberate cultivation. Self-propagating weeds are often regarded as unwanted plants from a human standpoint. Herbicides, often known as weedicides, are chemical substances that are

Name	Lipid (g/100 g)	Protein (g/100 g)	Ash (g/100 g)	Carbohydrate (g/100 g)	Total flavonoid (mg QE/g)	Ca (mg/g)	N (mg/g)	P (mg/g)	K (mg/g)	Na (mg/g)	Fe (mg/g)	References
Dheki	2.16	8.73	85.09	59.62	117.91	2.79	13.97	1.58	7.93	20.21	0.13	[91]
Hatisur	2.9	8.85	6.75	53.15	144.56	—	12.82	1.78	9.6	21.40	—	[83]
Takshak	5.26	9.44	7.29	58.24	109.52	—	15.11	1.53	6.21	19.97	—	[83]
Kulekhara	3.33	8.01	10.60	50.76	128.43	—	12.82	1.04	13.55	21.52	—	[83]
Gadabani	3.66	8.01	11.11	46.96	90.64	—	14.56	1.8	10.06	20.21	—	[83]
Helencha	2.66	16.69	12.46	61.61	—	9.02		—	12.53	1.35	0.23	[91]

Table 6.
Proximate composition of some selected weed species for their aptitude in cultivation.

Scientific name	Parts used	Common name	Family	Nutrient properties/traits	Region	References
Aerva leucura Moq	—	—	Amaranthaceae	—	Africa	[92]
Alternanthera sessilis (L.) DC	—	—	Amaranthaceae	—	Africa	[92]
Amaranthus sp.	—	—	Amaranthaceae	—	Africa	[92]
Amaranthus sp.	—	Wild amaranth	Amaranthaceae	Vitamin A; β-carotene, zeaxanthin, & lutein	Europe	[93]
Angelica sylvestris L.	Young stems	—	—	—	Europe	[94]
Anthriscus sylvestris (L.) Hoffm.	Young stems	—	—	—	Europe	[94]
Chondrilla juncea L.	Young shoots	—	—	—	Europe	[94]
Cichorium intybus L.	Basal leaves	—	—	—	Europe	[94]
Cirsium oleraceum (L.) Scop.	Young stems	—	—	—	Europe	[94]
Cochlearia officinalis	—	Scurvy-grass (Spoonwort)	—	Rich source of vitamin C	Europe	[93]
Crataegus monogyna Jacq.	Fruits	—	—	—	Europe	[94]
Crepis vesicaria subsp. haenseleri (Boiss. ex DC.) P. D. Sell	Basal leaves	—	—	—	Europe	[94]
Hibiscus sabdariffa	—	Sorrel	—	Vitamins A & C; Potassium; Antimicrobial	Europe	[93]
Malva spp.	—	Mallow	—	Vitamins A & C; Calcium, magnesium, iron, selenium, & potassium	Europe	[93]
Matricaria matricarioides/ discoidea	—	Pineapple weed	—	Pineapple like aroma	Europe	[93]
Mertensia maritima (L.) Gray	—	Oyster leaf	—	Tastes like oyster	Europe	[93]
Montia perfoliata, Claytonia perfoliata	—	Miner's lettuce (Winter purslane)	—	Vitamins C & A, & iron	Europe	[93]
Portulaca oleracea	—	Purslane	—	Omega-3 fatty acids	Europe	[93]
Portulaca oleracea L.	—	—	Portulacaceae	—	Africa	[92]
Quercus ilex subsp. ballota (Desf.) Samp.	Acorns	—	—	—	Europe	[94]

Scientific name	Parts used	Common name	Family	Nutrient properties/traits	Region	References
Reynoutria japonica	—	Japanese knotweed	—	Tastes like 'rain'	Europe	[93]
Rosa canina L.	Young shoots	—	—	—	Europe	[94]
Rumex crispus	—	Curly dock	—	Vitamins C, A, B1, & B2; Iron	Europe	[93]
Ruta graveolens	—	Rue (Common rue)	—	Strong-smelling leaves, bitter taste	Europe	[93]
Scorzonera laciniata L.	Tender leaves and stems	—	—	—	Europe	[94]
Sesamum c.f. angolense Welw.	—	—	Pedaliaceae	—	Africa	[92]
Silybum marianum (L.) Gaertn.	Peeled basal leaves	—	—	—	Europe	[94]
Smyrnium olusatrum	—	Alexanders (Alisander; Black lovage; Roman celery)	—	Aromatic, nutrient-dense; Celery-scented	Europe	[93]
Solanum nigrum L.	—	—	Solanaceae	—	Africa	[92]
Sonchus asper (L.) Hill	Peeled midribs	—	—	—	Europe	[94]
Stellaria media	—	Chickweed	—	Vitamins A, D, B complex, C, rutin; Calcium, potassium, phosphorus, zinc, manganese, sodium, copper, & iron	Europe	[93]
Taraxacum officinale	—	Dandelion	—	Flavonoids, cinnamic acids, & coumarins; Vitamins A, B, C, D, & K; folate, iron, calcium, & potassium	Europe	[93]
Trapa natans	Fruits	—	—	—	Europe	[94]
Trifolium spp.	—	Clover	—	Rich in protein, minerals, & carbohydrates	Europe	[93]
Urtica dioica	—	European nettles	—	Amino acids, protein, flavonoids; Iron, calcium, magnesium, potassium, & zinc	Europe	[93]
Viola sororia	—	Violet	—	—	Europe	[93]

Table 7.
Bioactive phytochemical profiling of above-ground parts of edible weed species available in Africa, Europe, and America.

Scientific name	Parts used	Common name	Family	Nutrient properties/traits	Region	References
Alliaria petiolata	—	Jack by the hedge/ Garlic mustard	—	Used for its garlicky aroma	Europe	[93]
Allium ursinum	—	Wild garlic	—	Garlic-like taste/flavor	Europe	[93]
Arum spp.	Bulbs	—	—	—	Europe	[94]
Bidens sp.	—	—	Asteraceae	—	Africa	[92]
Borago officinalis L.L.	—	Borage	—	Cucumber-like taste	Europe	[93]
Bunium bulbocastanum L.	Tubers	—	—	—	Europe	[94]
Cardamine hirsuta	—	Hairy bittercress	—	Vitamin C; calcium, magnesium, β-carotene, & antioxidants	Europe	[93]
Ceratotheca triloba (Bernh.) Hook.f.	—	—	Pedaliaceae	—	Africa	[92]
Chenopodium album	—	Lamb's quarters	—	Good source of fiber, protein, & vitamins A & C	Europe	[93]
Cichorium intybus	—	Wild succory	—	Vitamins B, C, K, & A; mineral salts	Europe	[93]
Cleome gynandra L.	—	—	Cleomaceae	—	Africa	[92]
Cleome monophylla L.	—	—	Cleomaceae	—	Africa	[92]
Commelina africana L. var. *ancispatha*	—	—	Commelinaceae	—	Africa	[92]
Commelina benghalensis L.	—	—	Commelinaceae	—	Africa	[92]
Corchorus olitorius L.	—	—	Tiliaceae	—	Africa	[92]
Crotalaria c.f. cleomifolia Welw. ex Bak.	—	—	Fabaceae	—	Africa	[92]
Cucumis c.f. anguria L.	—	—	Cucurbitaceae	—	Africa	[92]
Cynodon dactylon (L.) Pers.	Rhizomes	—	—	—	Europe	[94]
Elytrigia repens (L.) Desv. ex Nevski	Rhizomes	—	—	—	Europe	[94]
Equisetum arvense L.	Tubers, spring shoots	—	—	—	Europe	[94]

Scientific name	Parts used	Common name	Family	Nutrient properties/traits	Region	References
Eryngium spp.	Roots	—	—	—	Europe	[94]
Euphorbia oatesii Rolfe	—	—	Euphorbiaceae	—	Africa	[92]
Galinsoga parviflora	—	Gallant soldier (Quickweed)	—	Protein, calcium, & magnesium Antibacterial & anti-inflammatory	Europe	[93]
Hibiscus cannabinus L.	—	—	Malvaceae	—	Africa	[92]
Jacquemontia tamnifolia (L.) *Griseb.*	—	—	Convolvulaceae	—	Africa	[92]
Menyanthes trifoliata L.	Rhizomes	—	—	—	Europe	[94]
Ormocarpum kirkii S. Moore	—	—	Fabaceae	—	Africa	[92]
Plantago lagopus L.L.	—	Plantain	—	Polyphenolic compounds	Europe	[93]
Tithonia diversifolia (Hemsl.) A. Gray	—	—	Asteraceae	—	Africa	[92]
Tribulus sp. L.	—	—	Zygophyllaceae	—	Africa	[92]
Tricliceras longepedunculatum (Mast.) R. Fernandes var. longepedunculatum	—	—	Passifloraceae / Turneraceae	—	Africa	[92]

Table 8.
Bioactive phytochemical profiling of underground parts and other edible parts of edible weed species available in Africa, Europe, and America.

poisonous to plants and are used to eliminate undesired vegetation. They are specifically formulated to kill weeds.

Nevertheless, certain edible weed species are widely recognized for their advantageous role in enhancing food and nutrition security in rural communities such as *Amaranthus* spp., *Chenopodium* sp., *Cucumis* sp., etc. Edible weeds, unlike their counterparts that grow beyond farmers' fields, can be influenced by the use of herbicides. The reason for this is that herbicides, unlike hand weeding, are less discriminating and enable thorough removal of unwanted vegetation. The heightened utilization of herbicides may result in the eradication of edible weeds from food supplies, posing a potential threat to both ecological diversity and future sustainability. In this setting, TWEV offers significant opportunities to harness its potential by including several influential groups like academics, scientists, policymakers, social workers, extension services, and household decision-makers. An obstacle in considering the promotion and commercialization of weeds as a food source is the variation in how plants are categorized as weeds across different regions, which can differ from one country to another [95, 96]. Another significant obstacle in promoting the consumption of weeds is the necessity to alter people's perception of weeds from being regarded as a nuisance to being seen as a desirable, flavorful, and potentially healthy and cost-effective food source [97]. In essence, the goal is to alter individuals' perception of what is edible and delicious by highlighting the various edible weeds in our surroundings. This, in turn, has the potential to modify people's eating habits in a manner that is more sustainable for both themselves and the plants.

7. Conclusion

Weeds, often recognized as wild edible plants, have been extensively utilized for their culinary and therapeutic properties for an extended period. Currently, over one billion individuals worldwide incorporate weeds into their daily diet as veggies, particularly in poorer nations. In contrast, individuals in industrialized nations are currently "rediscovering" edible weed species for their culinary applications. These underutilized veggies contribute a diverse range of color, taste, and texture to their diet. In order to standardize the yield and nutraceutical values of these species, it is imperative to establish an effective large-scale growing method. By doing targeted research to enhance these characteristics and implementing effective marketing strategies, it is possible that these edible weed species could provide new lucrative prospects in the global agriculture industry. The nutritional and nutraceutical qualities of these weed species make them particularly appealing, given the growing interest among growers following the several cropping patterns of intercropping or cover crop with the main crops. Put simply, certain weed species that have been overlooked could potentially transform into valuable crops in the near future. Meanwhile, nonchemical weed control is a preferred method among several weed management choices. It holds significant importance in vegetable crops due to multiple reasons. Given the increasing worries about the development of herbicide-resistant weeds and the presence of pesticide residues in the edible portions of vegetables, it is imperative to explore sustainable and environmentally friendly methods for weed control in vegetables. One such approach is the transforming weeds into edible vegetables (TWEV). Several weed species have the capacity to provide nutrients, medical benefits, and exhibit a compatible growth pattern with the primary crop. Additionally, certain weed species are capable of suppressing other weeds in vegetable crops through their physical or allelopathic impacts. Yet, there is a significant absence of global recognition and adoption of weed species as viable sources of food. The presence of technological disparities and a dearth of location-specific experimentation could potentially explain this phenomenon. Implementing local-scale domestication, conducting experiments, and addressing technology limitations related to the TWEV can contribute to the widespread use of nutrient-rich weed species alongside major crops for sustainable weed management in vegetable production in the future.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 7

Induced Mutation: A New Paradigm in Pulse Weed Control Strategies

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Muhammad Sayyam Tariq and Mariyah Aslam

Abstract

Pulses hold a remarkable significance by providing affordable source of dietary protein and other vital nutrients. However, various biotic (weeds, pathogens, and insect infestation) and abiotic (temperature, nutrient stress, waterlogging, drought, salinity, and heavy metals) constraints induce substantial harm by decreasing its production. Weeds pose a significant global challenge as these not only compete with crop for vital resources such as sunlight, space, nutrients, and water but also attract other pests and pathogens that can harm the pulse crops. The weed–crop intervention varies significantly based on the crop type, topography, and soil characteristics. The implementation of chemical weed control strategies not only revolutionized the global agriculture but also widely acknowledged as an essential tool in accelerating crop productivity. Pre-emergent herbicides are easy to get in the market; however, the lack of post-emergence herbicides for certain pulses is of primary concern. The use of alternative weed control chemicals not just eradicates weeds but the risk of damaging the pulse crop may persist. The development of herbicide-resistant crop using modern techniques is the current objective of plant researchers. For this aim, induce mutation stands out the most cost-effective and reliable option, which can be accomplished using both physical and chemical mutagens.

Keywords: weed flora, herbicides, mutagens, seed mutagenesis, pulses

1. Introduction

The societal impact of agriculture is evident for upholding livelihood. Therefore, the role of agricultural sector in ensuring global food security is progressively expanding overtime [1]. Various emerging states are so anxious regarding their food security. The risk of decreased global food system is expected to intensify in the forthcoming decades due to the increasing population and the adverse impacts of climate change [2]. Meeting the growing demand for global food consumption in 2050 may require a robust increase in agricultural production, estimated to be around 60–70% by some sources such as Foley et al. and Tilman et al. Alternatively, other

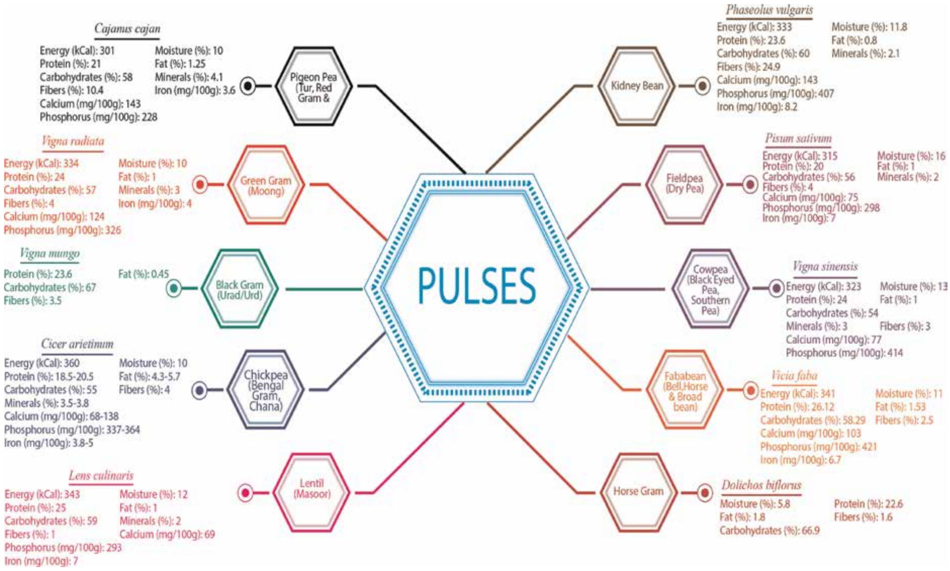

Figure 1.
Detailed overview on different pulse varieties along with their scientific name, common name, and nutritional profile.

studies suggest that food production might need to double by 2050 to adequately address the escalating needs [3].

Pulses are the edible seeds of plants associated with Fabaceae (a.k.a. Leguminosae or Legume Family), constituting one of the most extensive categories of flowering plants with high nutritional values. In the last decade, pulses have emerged as a sustainable choice to meet the rising demand for food. This upswing is perceived as a strategic approach to address the global agricultural challenges [4]. Based on chronological and archeological proof, it is indicated that the domestication and origin of pulses occurred in the America Presently, these are extensively enjoyed worldwide either as dietary staple or incorporated into various cuisine. Areas like Mexico, South and Central America, and various African countries have adopted the pulses as fundamental dietary components, with per capita consumption reaching up to 40 kg per year in certain regions [5]. Pulses emerge as an excellent protein source. Additionally, they supply dietary fiber, starch, minerals, and vitamins (**Figure 1**). Introducing pulses into your daily diet brings forth numerous health benefits, including the control of various metabolic conditions such as diabetes mellitus, coronary heart disease, and colon cancer [6]. While there is a diversity of pulses based on their varied shapes and sizes, although over 80 species contribute to the human diet and the FAO database encompasses only 11 of them [7] out of which chickpeas (*Cicer arietinum*), peas (*Pisum sativum*), lentils (*Lens culinaris*), mung beans (*Vigna radiata)*, dry broad beans (*Vicia faba*), moth beans (*Vigna aconitifolia*), lupins (*Lupinus perennis*), and mash bean (*Vigna mungo)* are widely accessible in the market [8].

1.1 Trends in global pulse cultivation

According to the current situation of global pulse production, Asia, Europe, and America collectively contribute to more than 80% of the world's output, with Asia alone contributing over 45% to the total. Additionally, Australia and African nations also contribute to the global production of pulses. Notably, higher production levels are observed in India, China, and Myanmar among Asian countries. India is leading as the primary producer of pulses. As of 2021, the worldwide pulse production reached a cumulative 88.97 million metric tons (Statista 2023) (https://www.statista.com/) from which peas, chickpeas, and dry beans collectively make up about 65% of the overall production of major pulses globally (**Figure 2**). Researchers have reported specific percentage shares for different varieties: dry beans (32%), peas (19%), chickpeas (14%), cowpea (7%), broad beans (7%), lentils (6%), and other varieties (15%) [9].

Weeds are the undesirable flora, detrimental for the optimum growth of plants [10]. Similar to crops, weeds require sunlight and water for photosynthesis, space in the soil for root proliferation, and essential nutrients derived from the soil to facilitate their growth. Consequently, weeds emerge as significant competitors with crops for vital resources [11]. Weed infestation poses a significant challenge in both developed and developing countries. Agricultural losses in developed countries typically fall within the range of 5–10%, whereas in developing or emerging countries, these losses increase to 20–30% [12]. Weeds often serve as alternate hosts for various diseases and insect pests (**Figure 3**) [13]. Hence, proficient weed control holds the potential to mitigate the risks of diseases and insect pest infestations in crops.

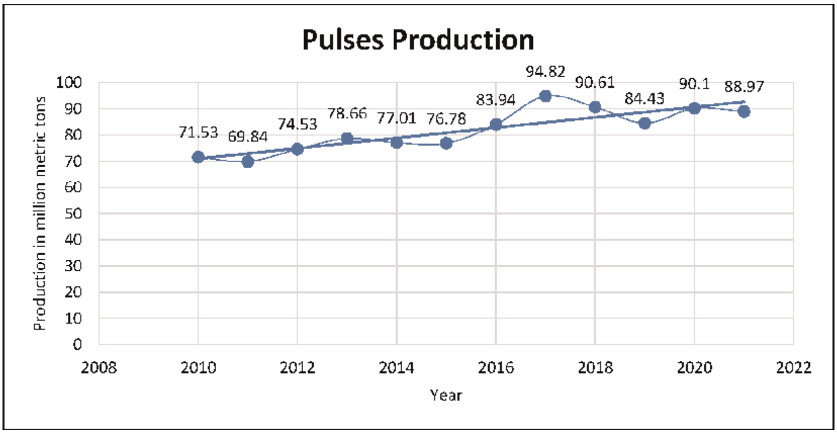

Figure 2.
Statistical overview showing worldwide pulse production from past 12 years (Statista 2023).

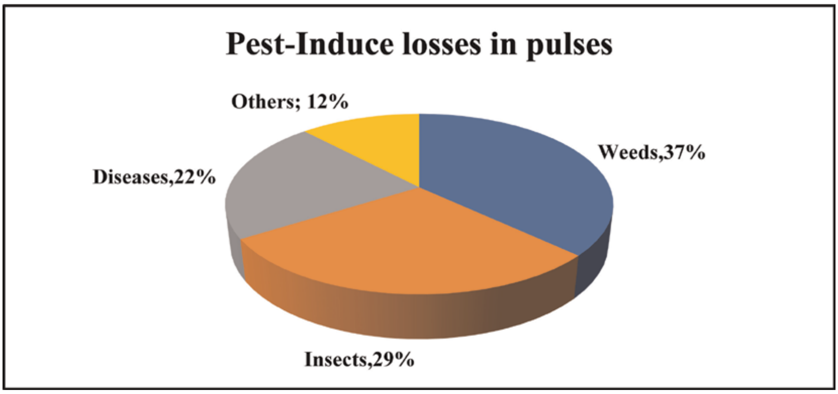

Figure 3.
Pest-induced losses in pulses.

Different pulse crops exhibit varied weed floras, including sedges, broadleaves, and narrow leaves. The type and intensity of weed infestation in field contribute to decline in pulse yield. Herbicides represent a chemical approach to weed control. However, the effectiveness of herbicides depends on dosage, timing, growth stage, and the specific crop being grown. Various commercially available herbicides not only eliminate weeds but also affect desired plants. Presently, researchers are concentrating on developing herbicide tolerance in pulse crops. The objectives for composing this book chapter are as follows:

- To highlight the diverse weed flora and its toxicity in different pulse crops.

- To present chemical method for weed management (its types, groups, merit, and demerits).

- The chapter also depicts the role of induced mutation to enhance the resilience of pulse crops against herbicidal treatments encompassing both physical and chemical mutagens.

- It also explores opportunities for integrating induced mutation techniques with other breeding strategies, such as genome editing, to improve the effectiveness of developing herbicide resistance traits in pulse crops.

- Finally, additional modern approaches in weed control strategies for pulses are discussed, which should be considered alongside induced mutation methods in near future.

2. Methodology

2.1 Search criteria and internet search engines

A detailed search was conducted using Google Scholar and Google Web Browser, employing keywords such as “pulses,” “impact of weeds on pulse crops,” “herbicide-resistant crops,” “herbicide mode of action,” “methods for developing herbicide-resistant crops,” “seed mutagenesis,” “herbicide resistance mechanisms,” “non-chemical weed control practices,” and “induced mutations for herbicide resistance in pulses.” Relevant and up-to-date literature was then carefully scrutinized based on the data relevant to this study. Papers that were outdated or lacked clearly defined results were excluded. A total of 66 peer-reviewed research articles were selected based on their content.

3. Discussion

3.1 Weed interference in pulse crop

Pulses face restricted productivity primarily from various biotic and abiotic factors, with weeds appear as a significant contributor by adversely impacting pulse crop yields. Upon analysis, it becomes evident that the losses in yield attributed to weeds are 34–37% compared to other pests or pathogens. The diversity and abundance of weed species in pulse crops are influenced by soil characteristics, farming practices, and climatic conditions [14]. Different pulses have specific critical periods when they are vulnerable to weed interference (**Tables 1** and **2**) [15].

Scientific name	Common name	Family	Emergence time	Weed type	Lifecycle
*Polypogon monspeliensis**	Rabbit Foot Grass, Green Foxtail, Lomarr Ghas, Beard Grass	Poaceae	Late–Mid October to March	Slender Leaf	Annual
*Avena fetua**	Wild Oat, Jangli Jai, Javdri				
*Sorghum halepense**	Jhonson Grass, Baaro				
*Echinochloa colona**	Jungle Rice, Swanki Ghas, Jharua, Barnyard Grass				
*Dactyloctenium aegyptium**	Egyptian Grass, Madhana Ghas				
*Phalaris minor**	Canary Grass, Bird's Seed Grass, Dumbi Sitti, Bunch Grass, Sittee Booti				
*Paspalum dilatatum**	Watre Grass, Naro Ghas				
*Lolium perenne**	Rye Grass, Rye Ghas				
*Cynodon dactylon**	Cynodon Dactylon, Khabal Ghas				
*Digitaria sanguinalis**	Large Crab Grass, Moti Khabal				
*Avena ludoviciana**	Wild Oats, Jaundhar				
*Lolium temulentum**	Poison Rye Grass, Ivary, Poson darnel				
Poa annua”	Guein, Buein, Sweet Grass, Annual Blue Grass, Annual meadow				
*Asphodelus tenuifolius**	Wild Onion, Piazi, Bhokat, Jangli Piyaz	Asphodelaceae	November–December	Slender Leaf	Annual
*Cyperus rotundus**	Nut Grass, Dela Ghas, Nut Sedge	Cyperaceae	November	Slender Leaf	Annual
*Allium canadense**	Wild Onion, Pyaazi	Amaryllidaceae	November–December	Slender Leaf	Annual

This table showcases the monocot weed flora in pulse fields, providing information on their scientific/common names, growing season, weed type, and family. (*) represents the weeds of rabi pulses such as chickpea, lentil, pea, and faba beans while (“) represents the weeds of kharif pulses like black gram, mung bean, cowpea, moth pea, pigeon pea, and kidney beans.

Table 1.
Monocot weed flora in pulse field.

Scientific name	Common name	Family	Emergence time	Weed type	Lifecycle
_Euphorbia peplus_*	Petty Spurge, Lal Dodhak, Cancer Weed, Radium Weed, Milk Weed	Euphorbiaceae	Mid October–Mid-March	Broad Leaf	Annual
_Euphorbia helioscopia_*	Mad Woman's Milk, Sun Spurge, Chatri Dodhak, Dhudi				
_Euphorbia hirta_*	Asthma Plant, Hairy Spurge, Ara Tanah				
Euphorbia simplex”	Kuargandal, Leafy Spurge				
Chrozophora tinctoria”	Dyer's Corton, Giradol, Turn Sole				
_Fumaria indica_*	Fumitory, Shihatara, Pitpapra, Fumewort	Papaveraceae	Late December	Broad Leaf	Annual
_Fumaria officinalis_*	Fumitory, Earth Smoke, Shahtara				
_Digera muricata_*	False Amaranth, Tandala	Amaranthaceae	Mid October-Late December	Broad Leaf	Annual
_Chenopodium album_*	Common Goosefoot, Baatho, Bathwa, Lambs Quarters				
_Amaranthus viridis_*	Slender Amaranth, Green Amaranth, Jangli Cholai, Pig Weed				
_Chenopodium murale_*	Fat Hen, Karond, Nettle Leaf				
_Gomphrena globose_*	Globe Amaranth				
_Chenopodium quinoa_*	Wild Quinoa				
Silybum marianum”	Milk Thistle, Kandyali Dodhak	Asteraceae	October to March	Broad Leaf	Mostly Annual some are Biennial and few are Perennial
Cirsium arvense”	Canada / Creeping Thistle, Field Thistle Leh, Kandyari				
Cichorium intybus”	Blue Daisy, Kasni				
Carthamus oxycantha”	Wild Safflower, Phooli, Kandiari				
_Parthenium hysterophorus_*	Santa Maria Feverfew, Famine Weed, Gajar Ghas, Dhanura				
_Sonchus asper_*	Spin Sowthistle, Kandiali Dodhak				
_Sonchus arvensis_*	Mil Weed, Perennial Sow Thistle, Gut weed				

Scientific name	Common name	Family	Emergence time	Weed type	Lifecycle
Gnaphalium purpureum”	Purple Cudweed, Spoon leaf purple everlasting				
Synedrella nodiflora”	Cinderella Weed, Nodeweed				
Solanum nigrum”	Black Night Shade, Mako/Peelak	Solanaceae	March	Broad Leaf	Annual–Biennial
*Corchorus tridens**	Wild Jute, Horn-Fruited Jute, Jangli Patsun	Malvaceae	December	Broad Leaf	Annual/Perennial
*Malva parviflora**	Dwarf Mallow, Cheese Weed, Mallow, Sonchal		October		
Melilotus indica”	Yellow Sweet Clover, Zard Seenji	Fabaceae	November–February	Broad Leaf	Annual
Lathyrus aphaca”	Crow Pea, Dokanni, Yellow Pea, Yellow Vetchling				
*Lathyrus sativus**	Grass Pea, Chraal, Kaseeri, White Pea, White Vetch				
Medicago polymorphav”	Bur Clover, Maina, Burr medic				
Melilotus alba”	White Sweet Clover, Sufaid Senji, Bukhara clover, honey clover				
Vicia hirsute”	Rewari, Hairy Vetch, Tiny Vetch				
*Medicago denticulate**	Maina, Toothed Bur Clover				
Trigonella polycerata”	Maini, Wild Fenugreek				
Vicia sativa”	Common Vetch, (Broad Leaf), Rewari, Choti Phali				
Lathyrus aphaca”	Crow Pea, Jangli Mattar				
*Coronopus didymus**	Swine Cress, Jangli Halon, Bitter Cress	Brassicaceae	November–January	Broad Leaf	Annual–Biennial
*Sinapis arvensis**	Wild Mustard, Jangli Sarsoon, Charlock Mustard, Field Mustard				
*Lepidium sativum**	Garden Cress, Halon, Cresss				
Sisymbrio irio	London Rocket, Khoob Kalan				
Ranunculus sceleratus”	Cursed Butterup, celery leaf buttercup	Ranunculaceae	Late January–March	Broad Leaf	Annual

Scientific name	Common name	Family	Emergence time	Weed type	Lifecycle
Argemone mexicana”	Satyanasi, Jangli Post, Mexican Poppy, Cardosanto				
_Stelleria media_*	Common Chickweed, Poolan Booti	Caryophyllaceae	Late December–February	Broad Leaf	Annual
Saponaria vaccaria”	Soapwort, Bara Takla, Cow Cockle, Cow basil				
Spergula arvensis”	Corn Spurry, Kalri Booti, Jangli Dhania				
Silene conoidea”	Chotta Takla, Forked Catchfly				
Arenaria serpyllifolia”	Thyme Leaf Sandwort				
Antirrhinum orontinum”	Wild Dog Flower Lesser snapdragon, Weasel’s snout	Plantaginaceae	January–February	Broad Leaf	Annual
Veronica agrestis”	Green Field Speedwell				
Anagallis arvensis”	Blue Pimpernel, Billi Booti	Primulaceae	January	Broad Leaf	Annual
_Convolvulus arvensis_*	Field Bindweed, Lehli, Hirankhuri	Convolvulaceae	Late December	Broad Leaf	Perennial
Rumex dentatus”	Broad Leaf Dock, Jangli Palak, Toothed Dock	Polygonaceae	January	Broad Leaf	Annual
_Polygonum plebeium_*	Prostrate Knotweed, Danak, Hazardani, Machechi, Common knotweed		Early November		
_Rumex spinosus_*	Kandiali Palak, Spiny Dock, Sorrel, Lesser jack		Late December		
Heliotropium europaeum”	Heliotrope, Ont Chara	Boraginaceae	January–March	Broad Leaf	Annual
Lithospermum arvense”	Stone Weed, Field gromwell, Bastard alkanet				
Tribulus terrestris”	Puncture Vine, Bhakra, Gokharu	Zygophyllaceae	Mid-Late February	Broad Leaf	Annual
Daucus carota”	Wild Carrot, Bishop’s Lace, Queen Anne’s Lace, Jangli Gajjar	Apiaceae	January	Broad Leaf	Biennial
_Trianthema portulacastrum_*	Desert Horse Purslane, Att Satt	Aizoaceae	Early October	Broad Leaf	Annual
_Cleome viscosa_*	Yellow Spider Flower, Tick Weed, Hulhul	Cleomaceae	Late October	Broad Leaf	Annual
_Galium aparine_*	Bed Straw, Couch Weed, Catch Weed,	Rubiaceae	October	Broad Leaf	Annual

Scientific name	Common name	Family	Emergence time	Weed type	Lifecycle
	Goosegrass, Warribooti, Cleavers				
Cannabis sativa"	Bhang, Indian Hemp	Cannabaceae	Late December–February	Broad Leaf	Annual
Oenothera laciniata"	Cutleaf Evening Primrose	Onagraceae	February	Broad Leaf	Annual

This table showcases the dicot weed flora in pulse fields, providing information on their scientific/common names, growing season, weed type, and family. (*) represents the weeds of rabi pulses such as chickpea, lentil, pea, and faba beans while (") represents the weeds of kharif pulses like black gram, mung bean, cowpea, moth pea, pigeon pea, and kidney beans.

Table 2.
Dicot weed flora in pulse field.

*3.1.1 Chickpea (*Cicer arietinum *L.)*

Chickpea (*Cicer arietinum* L.) ranks as the world's third most vital pulse crop enriched in protein and other vital nutrients. It faces persistent challenges in achieving optimal yield. Among various contributing factors, weed competition plays a pivotal role, causing significant yield losses ranging from 40 to 80%, depending on the severity of weed vegetation and the duration of the infestation. Due to its short stature and slow initial growth, chickpeas face intense competition from weeds, resulting in significant reductions in growth and yield [16]. The grain yield encounters a 17.1% decrease within the initial 30 days of sowing in chickpea as a result of weed competition, which increases to around 50% if weeds persist throughout the entire crop season. The initial 60-day period emerges as a critical phase marked by intense weed–crop competition in chickpea cultivation [17].

*3.1.2 Mung bean (*Vigna radiata *L.)*

Mung bean (*Vigna radiata* L.) is renowned for its exceptional nutritional value, digestibility, and non-flatulent attributes compared to other pulses [18]. The cultivation of mung beans faces significant challenges that can adversely affect production, with weed presence standing out as a major concern. The failure to manage weeds led to a substantial, 31% reduction in mung bean yield. The initial phase of land preparation plays a pivotal role in facilitating optimal plant growth. Weed control strategies involve a variety of approaches, including chemical measures such as the application of oxyflourfen pre-emergent herbicide at an early stage and manual weeding practices at specific growth stages. Oxyflourfen, employed as a pre-emergent herbicide, is utilized post-tillage and before seed planting to impede the growth or germination of weed seeds on the soil surface [19].

*3.1.3 Lentil (*Lens culinaris *Medik)*

Lentil (*Lens culinaris* Medik.), categorized as a minor grain legume, is increasingly gaining attention due to its significance as a vital dietary source of both macro and micronutrients, including essential amino acids. Beyond its nutritional richness, consumers value lentils for their appealing taste and ease of preparation. Although lentil production and consumption have been on the rise across Europe in recent decades, a considerable portion of the demand is fulfilled by imports from countries outside the European Union (EU) [20].

The robust interference of weeds in the initial stages of the lentil crop growth significantly hampers the plant's growth and development, resulting in reduced yield and overall quality. Depending on environmental conditions, weed diversity, and density, the associated losses can vary within the range of 20–80%. Conventional practices, including strategic sowing methods and timing, utilization of cover crops, implementation of crop rotations, and careful varietal selection, are routinely employed to impede weed growth and biomass, consequently enhancing lentil yields. Currently, herbicide treatments also demonstrate notably high effectiveness compared to other methods [21].

*3.1.4 Mash bean (*Vigna mungo *L.)*

Mash bean (*Vigna mungo* L.) stands out among leguminous crops, owing to its high protein and vitamin content, nutritional superiority, and rapid cooking time. Several factors contribute to the low yield of black gram, with weeds being identified as the most significant among them. The crop faces challenges in competing with weeds, particularly in its early stages of growth. Black gram is typically cultivated in rainfed conditions during the kharif season, where weeds emerge as a primary factor affecting crop productivity negatively. Weed competition during critical periods can lead to substantial yield reductions, ranging from 80 to 90%, depending on the type and intensity of weed infestation. Uncontrolled weed growth has been documented to result in a considerable reduction (46–53%) in black gram seed yield. Traditional methods like hand weeding are effective, and they are also expensive, labor-intensive, and time-consuming. As a response, weed control in black gram involves the application of mechanical, chemical, and biological methods, either individually or in combination with one another [22].

*3.1.5 Faba beans (*Vicia faba *L.)*

Faba bean (*Vicia faba* L.) holds significant importance as a primary food legume crop, serving as a valuable source of dietary protein. This legume is highly sensitive to shading especially during the pod emergence stage [23]. Faba beans face a considerable challenge from weeds, leading to yield losses ranging from 15 to 50% and contributing to annual global economic losses surpassing US$100 billion. The competition with weeds poses a significant obstacle to faba bean production, especially during critical developmental stages, resulting in substantial reductions in yield. The application of herbicides is widely recognized as the most effective strategy to address and reduce weed infestations [24].

*3.1.6 Pigeon pea (*Cajanus cajan *L.)*

Pigeon pea (*Cajanus cajan* L.) holds considerable significance within the realm of pulse crops. Globally, pigeon pea ranks fifth among grain legume crops [25]. Weeds are a major biotic factor that severely hampers pigeon pea yield, potentially leading to seed yield losses of up to 80 percent. The crop's slow initial growth has been associated with significant weed infestations, leading to suboptimal crop development and yield.

Consequently, effective weed management becomes a crucial factor in elevating the productivity of pigeon pea [26].

*3.1.7 Cowpea (*Vigna unguiculate *L.)*

Cowpea (*Vigna unguiculate* L.) stands as the foremost leguminous crop cultivated as pulse. Due to its slow initial growth, effective weed control becomes imperative during the early stages of crop development. The critical phase of competition between crop and weeds in cowpea occurs between 20 and 30 days after sowing (DAS). Prolonged competition throughout the season leads to significant yield reductions ranging from 40 to 90% in cowpea, depending upon various factors such as weed intensity, weed species, season, location, and prevailing climatic conditions. Different cultural methods, including mulching, manual weeding, and stale seedbed, can be employed for weed control in cowpea. However, the chemical method of weed control emerges as the most economical and viable option for managing weeds in cowpea [27].

*3.1.8 Kidney beans (*Phaseolus vulgaris *L.)*

The kidney bean or common bean (*Phaseolus vulgaris* L.) named for its resemblance to a human kidney holds immense nutritional value and is a vital pulse crop cultivated throughout the year. Numerous field experiments have shown substantial yield losses in common bean, ranging from 60 to 80%, when weed control is delayed after the emergence of the crop [28]. To tackle weed invasions, manual weeding is commonly employed. However, due to a shortage of labor during crucial periods and the increased wages of laborers, farmers seek more convenient and cost-effective alternatives. An integrated weed management approach, which combines low-dose herbicide application with manual weeding, is preferable. This not only ensures effective weed control but is also environmentally favorable [29].

*3.1.9 Garden pea (*Pisum sativum *L.)*

Peas (*Pisum sativum* L.) belong to the legume family, holding significance in both human and animal nutrition. Garden peas have been a dietary staple for millennia, offering a rich source of protein based on their utilization and consumption patterns [30]. Weed management becomes crucial seeing that field peas exhibit weaker competition with weeds compared to certain other species. The impact of weeds can result in yield losses ranging from 40 to 70% in garden pea cultivation. In situations with weed challenges, implementing integrated practices such as increased seeding rates and selecting appropriate cultivars can enhance the competitive edge of field peas, particularly in organic production [31].

4. Herbicides-a mid-20th century breakthrough

Herbicides, also known as weed killers, anti-weed agents, or weed eliminators, are effective chemicals employed for the control of unwanted plants in agriculture, contributing to enhanced crop production. Herbicides had a deep-rooted history dating back to ancient agricultural practices, where natural products like salt and olive oil were used. The mid-20th century witnessed a significant milestone with the introduction of synthetically manufactured herbicides. Sinox (Sodium dinitrocresylate), the first major organic chemical herbicide, emerged in France in 1896. In the late 1940s, new herbicides, stemming from research during World War II, marked the beginning of the "miracle" weed killer era. Within two decades, over 100 new chemicals were synthesized, developed, and deployed. The intensification of production, characterized by increased fertilizer usage, monocultures, and the cultivation of shorter crop varieties, commenced in the 1960s, resulting in heightened agricultural yields. Nevertheless, this also created favorable conditions for weed proliferation [32]. Since 1990, the global application of herbicides to agricultural land has experienced a surge of more than 260%, currently surpassing an annual quantity of 3 million tons [33].

Herbicides exhibit diverse classifications, which owing to the chemicals they contain, application methods, site of action, and timing of application. The mode of action for herbicides is a systematic, step-by-step process associated with herbicide treatment. Each herbicide's mode of action is linked to a specific target site, often referred to as a mechanism of action [34]. Here are some of the classification outlining various types of herbicides [35]:

1. Specificity-based Classification:
    - Selective Herbicides
    - Non-Selective Herbicides
2. Method based on Application:
    - Soil-Applied Herbicides
    - Foliar-Applied Herbicides
3. Time of Application:
    - Pre-Plant Herbicides
    - Pre-Emergence Herbicides
    - Post-Emergence Herbicides

The process of herbicide application involves several distinct stages in its mode of action. Initially, the herbicide is applied, making direct contact with the plant. After application, the herbicide is absorbed by the plant. As the herbicide permeates the plant's body, it moves to various plant areas, creating toxicity that ultimately results in the plant's demise. Herbicides entering plants or weeds undergo metabolic changes influenced by compound properties, plant chemical composition, and the plant's metabolic capacity. Tolerant plants can deactivate herbicides. Herbicides are commonly classified into different groups, each with specific modes of action [36].

- *Group 1*, ACCase inhibitors hinder lipid formation in roots and growing points and are primarily used post-emergence against grasses.

- *Group 2*, ALS/AHAS inhibitors disrupt amino acid synthesis, leading to plant death, and are applied post-emergence.

- *Group 3*, Microtubule assembly inhibitors impede cell division in plant parts and are applied pre-germination.

- *Group 4*, Synthetic auxins disturb cell growth in developing stems and leaves, applied to actively growing plants.

- *Group 5*, Photosynthetic inhibitors at Photosystem II Site A obstruct photosynthesis, used pre/post-emergence.

- *Group 7*, Photosynthetic inhibitors at Photosystem II Site B also hinder photosynthesis at a different site.

- *Group 9*, EPSP synthesis inhibitors block amino acid synthesis via the shikimate pathway, with broad-spectrum effects.

- *Group 10* contains glutamine synthesis (GS) inhibitors, acting nonspecifically on nitrogen metabolism, leading to the accumulation of ammonia and disrupting cell functions and metabolic processes.

- *Group 15* consists of cell growth and division inhibitors, applied through soil or foliar methods.

- *Group 22*, Cell membrane disruptors or PPO inhibitors target the cell membrane, disrupting its structure, and can be applied both pre and post the plant's growth stage.

- *Groups 12, 13, and 27* collectively known as pigment synthesis inhibitors, specifically target carotenoids, earning them the name carotenoid synthesis inhibitors. These herbicides also damage chlorophyll structure, giving rise to their colloquial name, bleachers, as they eliminate the natural green color of plants and render them white.

Nonetheless, the prolonged application of herbicides with the same pattern can lead to the emergence of herbicide-resistant weed ecotypes resulting in higher dosage of herbicides application [37].

4.1 Herbicide resistance in weeds

Herbicides play a crucial role in weed control, offering a time and labor-saving solution that significantly contributes to global food production. Despite their efficiency in managing weeds, the persistent use of herbicides is heightened concern across the world by the reason of the development of herbicide resistance in numerous weed species while crops bear a high susceptibility to herbicidal impact. Phytotoxic symptoms induced by herbicides in plants are characterized by leaf and shoot abnormalities, root and shoot stunting, the formation of leaf spots, chlorosis (yellowing of leaves), and necrosis (death of leaves). Moreover, herbicides can lead to oxidative damage, growth inhibition, interference with water and nutrient uptake, and disruption of the photosynthesis process [38]. Therefore, there is a significant demand for the advancement of crops that display resistance to herbicides. Data from the International Herbicide-Resistant Weed Database reveals a substantial increase in the evolution of weed species since the first documented case of herbicide resistance for triazines in 1970 [39]. Over time, the total number of herbicide-resistant weed species has increased dramatically, with developing resistance to 21 out of 31 known herbicide action sites and 165 different herbicides. Presently, herbicide resistance has been observed in 96 crops across 72 countries, with a global total of 513 reported cases involving 267 weed species [40]. Brosnan et al. documented the development of resistance in common turfgrass weeds like annual bluegrass and goosegrass to PSII-inhibiting herbicides and dinitroaniline herbicides [41]. Ghanizadeh et al. suggested that *Chenopodium album* may have developed resistance due to significant selective pressure from repeated applications of triazines in consecutive maize crops. Additionally, subsequent investigations uncovered the presence of dicamba-resistant *C. album* in maize fields. *Solanum nigrum*, a problematic weed in numerous pea and sweet corn fields and *Persicaria maculosa*, also exhibited resistance to triazines. *Stellaria media* displayed resistance to acetolactate synthase (ALS)-inhibitor herbicides. More recently, a population of *Lolium perenne* was identified as resistant to multiple ALS-inhibitors. ACCase-inhibitor resistance was observed in populations of both *Avena fatua* and *Lolium multiflorum* [42]. Heap et al. documented that *Lolium rigidum* retains its status as the most problematic herbicide-resistant weed globally, with *Amaranthus palmeri, Conyza canadensis, Avena fatua, Amaranthus tuberculatus*, and *Echinochloa crus-galli* following closely behind [43].

This trend emphasizes the need for sustainable approaches to weed management in agriculture. Herbicide resistance in agriculture is closely linked to the practice of intensive monoculturing, where various crops are commercially produced. Specific active ingredients within herbicides show a heightened occurrence of resistant weed species globally, particularly associated with monoculture farming systems. For example, Atrazine, which inhibits photosynthesis at photosystem II, has shown resistance in 66 different weed species across different crops. Glyphosate, an inhibitor of EPSP synthase, is now resistant for 57 different weed species, including pulses like chickpea, lentil, peas, and beans. Additionally, inhibitors of acetolactate synthase such as Tribenuron-methyl, Imazethapyr, Imazamox, Metsulfuron-methyl, Chlorsulfuron, Iodosulfuron-methyl-sodium, Bensulfuron-methyl, Thifensulfuron-methyl, and Mesosulfuron-methyl are no longer effective for controlling 45, 44, 40, 39, 38, 38, 29, 29, and 26 different weed species in various cash crops, including cereals and pulses. Moreover, the herbicide class Fenoxaprop-P-ethyl, acting as an inhibitor of fat synthesis and acetyl coA carboxylase, faces resistance in 33 different weed species. Paraquat and Simazine, known for reducing photosynthetic activity at photosystem I and II, respectively, encounter resistance in 31 different weed species. The synthetic auxin 2–4-D, also recognized as a plant cell growth disruptor, has developed resistance in 25 weed species (**Figure 4**) [44].

4.2 Impact of herbicide application on crops

As previously discussed, over time, various weeds have developed resistance to different formulations of herbicides. Consequently, while weeds have rapidly evolved to resist chemical herbicides, our crops have fallen behind, resulting in a continual decline in yields. In pulses, the prevailing method for weed control typically consists of applying pendimethalin as pre-emergent (PRE) weedicide followed by manual

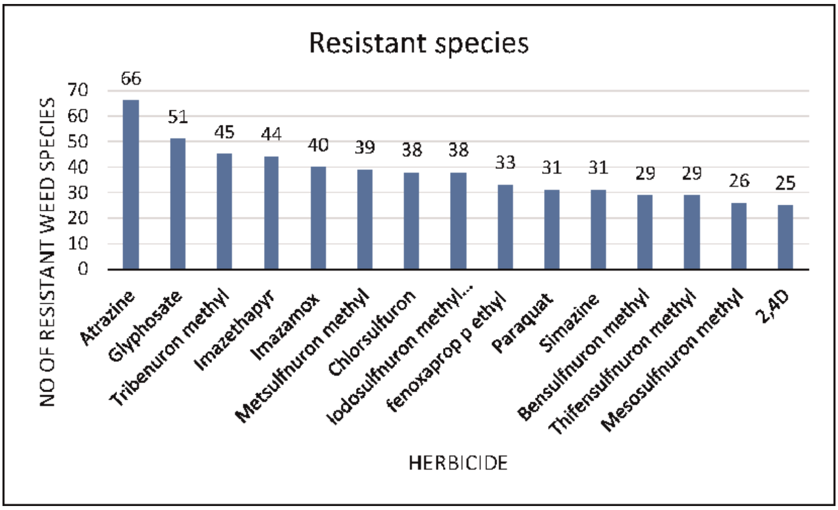

Figure 4.
Top 10 herbicides and the corresponding number of resistant species they are linked to [15].

weeding. However, this strategy falls short in managing subsequent weed flushes occurring approximately 1 month after sowing. As a result, post-emergence (POST) herbicides become necessary, yet there is not a specific herbicide recommended, especially for controlling broad-leaved species. Consequently, farmers turn to various commercially available herbicides for post-emergence application, which not only eradicate weeds but also impact desired plants [45]. To address this challenge, researchers are focusing on developing herbicide tolerance in pulse crops. It became necessary to manipulate the genetic composition of crops, which could be achieved through either recombinant DNA technology or mutation. Recombinant DNA technology was first utilized by Cole in 1994. Nowadays, the tobacco plant serves as a model plant for studying and optimizing the performance of alien genes. However, this technique has not proven to be significantly beneficial, as it involves various socioenvironmental risks and genetically modified plants themselves may not be safe. Careful management is required, which may be unsatisfactory [46]. In such circumstances, only mutation can introduce diverse genetic variations needed to achieve our objectives.

5. Development of herbicide-resistant crop via mutagenesis

In the light of the fact that the herbicides have long been the preferred method for effectively managing weeds and increasing crop productivity; however, the challenge lies in selectively eliminating weeds while ensuring the ultimate protection of desired plants. The development of herbicide resistance has become a desirable trait, particularly in various commercial crops. Thanks to the advancement in biotechnology, genetic engineering is predominantly employed, involving the selective mutations or the insertion of foreign genes making it possible to create herbicide-tolerant crops (HTCs) that mitigate significant yield losses. Over the past few decades, numerous genes have been identified that confer herbicide tolerance in valuable crops. This tolerance can result from mutations in native genes or the introduction of foreign genes to generate transgenic plants. Currently, various research initiatives and findings actively focused on the development of herbicide-resistant crops, with induced mutation emerging as a prominently highlighted method. Mutagenesis has emerged as a well-established technique in plant breeding, serving to complement available germplasm and enhance cultivars in specific traits. It effectively boosts genetic variability for crop improvement [47]. There are primarily three types of mutagenesis employed in mutation breeding:

- *Induced Mutagenesis:* This involves the use of radiations such as X-rays, gamma rays, or ion beams, as well as chemical mutagen treatments to induce mutations.
- *Site-Directed Mutagenesis:* This method is employed to deliberately create specific mutations at targeted sites within a DNA molecule. It is predominantly conducted through PCR-based techniques, including traditional PCR and inverse PCR.
- *Insertion Mutagenesis:* This process involves the creation of mutations through DNA insertion. This can occur through genetic alteration and t-DNA insertion or by activating a transposable agent [48].

Mutagenic agents such as radiation and specific chemicals are utilized to induce mutations. Physical mutagens, such as gamma rays, and chemical mutagens like ethyl methanesulfonate (EMS), ethyl nitrosourea, N-nitroso-N methyl urea, and sodium azide play a crucial role in this process.

5.1 Physical agents

Ionizing physical mutagens like gamma rays, x-rays, neutrons, and high-energy ions produce reactive free radicals that interact with DNA, causing chromosome deletions, rearrangements, and base loss, altering the structure and function of proteins and thereby modifying phenotypes. Gamma rays, particularly noted for their deep penetration, are extensively utilized. Plant breeders have generated valuable mutants of both Kabuli and Desi cultivars of chickpea using gamma rays and FN irradiation, respectively (**Table 3**) [49].

5.2 Chemical agents

Chemical mutagenesis represents a basic and reliable approach for generating mutations. Agents like sodium azide, 1-methyl-1-nitrosourea (MNU), and diethyl

Ionizing agent	Merit	Demerit	Citations
Gamma Rays (γ)	Higher energy and deep penetration in plant tissue	Cannot create mutation in specific location of the genome and time consuming	[50]
Ultraviolet Rays (UV)	Strong genotoxic effect	Low penetration power and time consuming	[51, 52]
Fast Neutrons (FN)	Delete multiple gene at same time	Target site in the genome is not specified	[53]

Table 3.
Various ionizing agents and their respective merits and demerits.

sulfate have the capacity to induce mutations, with plant breeders predominantly favoring alkylating agents for this purpose [54]. This method often leads to a high frequency of nucleotide substitutions, with the majority (70–99%) of alterations in EMS-mutated populations involving transitions from GC to AT base pairs. Additionally, combinations of sodium azide (Az) and methylnitrosourea (MNU) are utilized, capable of inducing shifts in either direction, from GC to AT or from AT to GC. The dosage of a chemical mutagen primarily hinges on factors such as concentration, treatment duration, and treatment temperature. Various modifying factors, including pre-soaking, solution pH, metallic ions, carrier agents, post-washing, post-drying, and seed storage, also play significant roles. It is important to note that all these chemical mutagens are highly carcinogenic, necessitating extreme caution during handling and disposal [55].

5.3 Origin and history of mutagenesis

The origins of mutation induction can be traced back to around 300 BC in China, where early accounts of mutant crops emerged. However, significant advancements have been made over time to increase the frequency of mutations from ancient times to the present day. During the 1950s, 1960s, 1970s, and 1980s, activities related to mutation induction reached their peak, resulting in notable achievements such as the release of various mutant varieties. Numerous countries, such as China, India, Pakistan, Bangladesh, Vietnam, Thailand, Italy, Sweden, the United States, Canada, and Japan, have extensively utilized induced mutagenesis and mutation breeding to develop superior mutant varieties across a diverse array of important agricultural crop species. These include cereals, pulses, oilseeds, vegetables, fruits, fibers, and ornamentals [47]. Imidazolinone resistance is commonly developed in plants using mutagenesis, and these tolerant varieties, particularly those resistant to imidazolinones, have become frequently reported. The first commercialized HTC emerged in 1996, and currently, over 87.5 million hectares of land worldwide are planted with herbicide-tolerant crop varieties, constituting more than 45% of the total land area dedicated to mutant crop varieties. Various HTCs have been developed and commercialized against different herbicides. Examples include soybean, wheat, sunflower, and rice developed against ALS inhibitors, branded as Clearfield by BASF. Notably, these varieties are non-transgenic and are cultivated globally [56, 57]. Registered mutants are classified into different groups based on their enhanced characteristics or traits. These categories encompass agronomic traits (49%), quality traits (20%), yield or yield-related parameters (18%), biotic challenges (9%), and abiotic stresses (4%) [58].

5.4 Seed mutagenesis

Seed mutagenesis is primarily employed in sexually propagated plants, with seeds being the most frequently used plant material for inducing mutations due to their remarkable tolerance to harsh physical conditions (abiotic/biotic). While treating seeds, the dose that inhibits approximately 50% germination (LD50), is typically employed to achieve favorable outcomes. However, both the dosage and application duration of a mutagen vary depending on the plant species and must be determined through experimental investigation [59]. The protocol spans 3 days and comprises three main steps [60]:

1. Soaking seeds in water beforehand

2. Preparing the EMS solution and conducting mutagenesis and

3. Eliminating EMS, washing the seeds with a deactivating solution and water, and then proceeding to plant them.

Efforts have been underway for an extended period to cultivate imidazolinones/-sulfonylureas-resistant crops through seed mutagenesis, demonstrating success in crops such as soybean, sunflower, wheat, corn, lentil, and canola. These crops are classified as non-transgenic because their tolerance/resistance has been achieved through the application of physical and chemical mutagens. Seed mutagenesis, widely employed in the selection process, has been crucial in developing herbicide resistance or tolerance in plants. These mutagenic agents are not limited to seeds but are also applicable to pollen. Among chemical mutagens, EMS has proven to be highly effective. Additionally, gamma radiation has been employed in seed mutagenesis, irradiating two lentil cultivars at doses of 90, 100, and 110 Gray to confer plant tolerance/resistance against chlorsulfuron herbicide. For plants with limited or absent seed production, mutagenesis can be applied to tissues (**Figure 5**) [61].

5.5 Achievements of mutation breeding

The mutant varieties have shown improvements across diverse traits, encompassing increased yield, accelerated maturity, enhanced quality, and greater resilience to both biotic and abiotic stresses. Mutation breeding, unlike conventional methods, offers a potent means to introduce variability and facilitates the selection and genetic enhancement of pulse crops with limited genetic diversity. Globally, a total of 331 pulse crop varieties have been released through mutation breeding, with

Figure 5.
Re-sprouting of chickpea mutant resistant to roundup.

India leading the count with 122 varieties (excluding legumes like soybean and groundnut). Among pulse crops in India, the highest number of mutant varieties has been released for mung bean (34), followed by black gram (18), cowpea (16), chickpea (12), pigeon pea (12), moth bean (11), Lablab (6), lentils (4), horse gram (6), peas (2), and common bean (1) [62]. Induced mutagenesis, alongside related breeding strategies, possesses the capacity to enhance both quantitative and qualitative attributes in crops within a significantly shorter timeframe compared to traditional breeding methods. The widespread adoption of mutation breeding-derived agricultural varieties worldwide underscores its potential as a versatile and efficient approach applicable to various crops [63]. Various researchers have been independently focusing on different pulse crops, aiming to induce resistance against herbicides through mutation such as.

Singh et al. conducted a study on the sensitivity of lentil (*Lens culinaris* L.) to post-emergence herbicides, highlighting the need for the development of herbicide-tolerant cultivars. In the absence of natural variability, they employed mutation breeding as a powerful tool to introduce variability for desired traits in lentil. Specifically, 1000 seeds of the lentil genotype (LL1203) were subjected to gamma radiation (300 Gy, ^{60}Co) with the aim of inducing herbicide tolerance. Seeds of persisting M1 plants were individually harvested and divided into two parts to generate the M2 population, which was then subjected to herbicide application using imazethapyr and metribuzin. Data were collected for herbicide-tolerant M2 plants, including pod characteristics and yield per plant. The findings of the study indicated that metribuzin-tolerant mutants exhibited additional desirable traits, suggesting their potential utility in lentil breeding [64].

As per Toker et al., chickpea (*Cicer arietinum* L.) encounters an unresolved issue of sensitivity to various herbicides, including imidazolinone (IMI). In an effort to address this challenge, they employed induced mutagenesis to select for resistance to IMI across multiple Cicer species. The seeds were irradiated with gamma rays at doses of 200, 300, and 400 Gy from a 60Co source. Several dominant mutants were identified in the M1 generation, and these were subjected to a progeny test in the M2 generation. In the field application, the recommended dose of IMI was increased tenfold, and through this process, a highly IMI-resistant mutant of *C. reticulatum* was isolated [65].

Rizwan et al. provided a summary indicating that the lentil crop (*Lens culinaris* L.) exhibits a high sensitivity to herbicides, prompting a study aimed growing of herbicide-resistant mutants through chemical-induced seed mutagenesis. Three advanced genotypes were subjected to treatment with varying concentrations of ethyl methanesulfonate (0.1 and 0.2%), hydrazine hydrate (0.02 and 0.03%), and sodium azide (0.01 and 0.02%). The newly developed M2 population was assessed for resistance against two different herbicides, Ally Max and Atlantis. Across all environments, a total of 671 resistant mutants were identified. Recognizing the significance of these herbicide-resistant mutants, it is recommended that further evaluation be conducted at higher doses under controlled environmental conditions. The study could be advanced until the release of a new commercial herbicide-tolerant lentil cultivar [66].

In 2021, Galili et al. demonstrated that imidazolinone herbicides manifest a broad spectrum of weed control, yet chickpea plants display sensitivity to acetohydroxyacid synthase (AHAS, also known as acetolactate synthase [ALS]) inhibitors. Through the utilization of the chemical mutagen ethyl methanesulfonate (EMS), a chickpea line (M2033) was generated, displaying resistance to imidazolinone herbicides [67].

Hamid et al. also made significant contributions to their study by screening and assessing the tolerance of 145 mutagenized lentil genotypes at the M5 generation to imazamox herbicide. This included the evaluation of 139 M5 lentil genotypes derived from seeds mutagenized with ethyl methane sulfonate (EMS). Among these, five genotypes demonstrated notable tolerance to the herbicide [68].

5.6 Current advancements in induced mutagenesis

Previously, traditional methods of induced mutation played a crucial role in enhancing the resistance of crops to herbicides, but they were laborious and time-consuming. With the advent of transgenic techniques over the past few decades, significant progress has been made in crop improvement, leading to a substantial increase in transgenic herbicide-resistant crops. Genome editing by the modification of target DNA sequences through various methods such as addition, substitution, or selection of nucleotides emerging as a prominent method complementing mutation breeding efforts. This is achieved through technologies including zinc-finger nucleases (ZFNs), transcriptional activator-like effector nucleases (TALENs), base editors, clustered regularly interspaced short palindromic repeats associated with the Cas9 system (CRISPR/Cas9), and Primer Editors. These tools offer robust capabilities to enhance crop resilience against diverse challenges. Among them, CRISPR/Cas9 technologies are widely recognized as the most efficient and versatile genome editing tools [69]. Researchers have engineered herbicide-tolerant wheat crops by employing zinc-finger nucleases (ZFNs) after target the TaALS gene. Likewise, herbicide-tolerant rice and potato varieties have been developed through the use of TALENs, targeting the OsALS1 and SlALS1 genes, respectively [70].

The discovery of CRISPR/Cas genetic editing tools in 2012 paved the way for significant biotechnological and genomic advancements, enabling the rapid breeding of plants with desired traits such as increased yield, nutritional value, stress tolerance, and resistance to pests and herbicides. Numerous crop varieties, such as rice, maize, soybean, Arabidopsis, tobacco, cassava, flax, potato, and rapeseed [70], have been transformed as herbicide-resistant through the utilization of the CRISPR/Cas system. Despite its simplicity, flexibility, and high specificity, challenges remain in fully realizing the potential of CRISPR/Cas-mediated genome editing for crop improvement. Although progress has been made in creating herbicide-resistant crop germplasms, success has been primarily observed in resistance to specific types of herbicides, such as ALS-inhibiting and ACCase-inhibiting herbicides, as well as glyphosate. However, challenges persist in effectively controlling weeds resistant to other types of herbicides, such as 4-hydroxyphenylpyruvate dioxygenase and protoporphyrinogen oxidase inhibitors. Furthermore, while non-selective herbicides like glyphosate and glufosinate have broad-spectrum herbicidal properties, research on enhancing crop resistance to these herbicides is limited. Efforts in herbicide-resistant crop development primarily concentrate on selective herbicides, and there is a need for research into breeding crops resistant to multiple herbicides simultaneously. Thus, the development of non-selective herbicides or multiple herbicide-resistant crops remains an important focus [71].

These techniques have not yet been applied to develop herbicide-resistant pulse crops, indicating the need for its implementation in pulse crop breeding. While certain herbicide-resistant traits have been successfully introduced using this technology, further research is needed to address remaining challenges, particularly regarding the development of crops resistant to a broader range of herbicides.

6. Systemic approaches for chemical-free weed management

The adoption of agricultural methods such as organic farming or regenerative farming, which prioritize mechanical and cultural weed control measures over herbicide use, is on the rise. Therefore, successful weed management does not solely depend on the utilization of herbicides. Several methods are available for weed control that excluding the use of herbicides [32]. These include practices such as

1. Soil solarization
2. The stale seedbed technique
3. Crop establishment methods
4. Adjusting the crop planting date
5. Modifying crop density
6. Managing fertilizers
7. Incorporating cover crops
8. Intercropping
9. Mulching
10. Crop diversification.

Soil solarization, an environmentally friendly technique, has demonstrated effectiveness against various annual weeds, including annual bluegrass, Ageratum spp., Amaranthus spp., barnyard grass, cogongrass, common purslane, *Digitaria* spp., *Portulaca* spp., redroot pigweed, *Setaria* spp., and others. The stale seedbed technique proves successful against weed species with seeds primarily located in the topsoil, those with low initial dormancy, and seeds dependent on light for germination. Weed species susceptible to this technique include *Cyperus iria*, *Digitaria ciliaris*, *Eclipta prostrata, Leptochloa chinensis*, and *Ludwigia hyssopifolia*. The bed planting technique resulted in a 12.5% reduction in the population of Phalaris minor compared to flat sowing. Additionally, crop geometry, such as row spacing and planting patterns, significantly influences the competition between crops and weeds. Narrow row spacing, like 15 cm, led to a 16.5% reduction in Phalaris minor biomass compared to the standard spacing of 22.5 cm. Intercropping provides numerous advantages to a farming system. In an experiment, maize + blackgram (1:1) intercropping demonstrated lower total weed density and weed dry weight compared to other intercropping systems. Combining maize + blackgram intercropping with the application of pendimethalin at 0.75 kg per hectare, applied pre-emergence 3 days after sowing (DAS) and one-hand weeding 25 DAS, resulted in higher weed control efficiency. Including pulses as an intercrop in jute cultivation effectively suppressed dicot and sedge weeds by up to 54%. Mulches serve as effective tools for weed control. Increasing the mulch rate to 5.0 or 7.5 tons per hectare resulted in a reduction in weed biomass for various species. It reduced the emergence of grass, broadleaf, and sedge species by varying percentages. For instance, *Phalaris minor*, *Oxalis corniculata*, *Medicago sativa*, and *Setaria glauca* showed reduced biomass by 26–46%, 17–55%, 22–43%, and 26–40%, respectively [72].

6.1 Recently developed practices in weed management

6.1.1 Laser technique

In addition to conventional methods, advanced technologies such as laser weeding are now being implemented. A novel approach involves treating weeds using multiple laser beams without causing harm to non-target plants. Laser treatment effectively eliminates weeds by employing a high-energy laser beam that can either cut, burn, or release sufficient energy to inhibit their growth. The success of laser weed treatment is contingent upon factors such as wavelength, laser power, exposure time, and spot size. Currently, this method is being applied to carrots, cauliflower, and broccoli with sub-millimeter precision, enabling the elimination of up to 200,000 weeds/h. Experimental trials involving lasers have been conducted on common chickweed, scentless mayweed, and oilseed rape, demonstrating varying levels of susceptibility. Notably, certain species, such as *B. napus*, exhibit lower sensitivity to laser treatment and necessitate higher doses for effective weed control [73]. Although promising developments have been made with carbon dioxide laser radiation, these techniques are still in the experimental phase [74].

6.1.2 Thermal application

Utilizing thermic approaches has proven effective in rapidly managing weeds through various methods such as fire, flaming, hot water, steam, and freezing. Flaming, a commonly employed technique utilizing propane gas burners or renewable alternatives like hydrogen, achieves combustion temperatures of up to 1900°C [75]. This process leads to the destruction of plant membranes, causing a loss of cell function and ultimately resulting in the death or severe weakening of the plants. Flaming is particularly effective in controlling erect and broad-leaved weeds during their early growth stages, while its efficiency is relatively lower in managing grassy and prostrate weeds [76].

6.1.3 Robotics

Revolutionary agricultural robots are making their way into the market, with 22% specifically tailored for weed control. In the autonomous weeding domain, these robotic systems employ diverse methods for plant destruction, including cultivation, crushing, spot-spraying, electric shocks, lasers, and high-intensity light [77]. These systems incorporate computer vision techniques to identify and eliminate weeds in agricultural fields. Controlled effortlessly through a mobile app, this user-friendly robot is detailed by the authors, exploring its hardware and software components, encompassing cameras, motors, and microcontrollers. Field tests assessing the robot's performance yielded results indicating a success rate of over 90% in detecting and removing weeds but farmers not widely embrace this technique [78]. Presently, this approach is being implemented on carrots and sugar beets, resulting in a weed control rate of 93.86% [73].

6.1.4 Unmanned aerials vehicles (UAVs)

UAVs represents an efficient and environmentally friendly approach to site-specific weed management. This technology allows for precise and continuous monitoring and mapping of weed infestations, achieved through the integration of UAVs with GPS technologies and advanced cameras and sensors capable of identifying specific weeds. Renowned for its excellent control capabilities in the presence of obstacles, this technique boasts advantages such as no soil compaction and minimal labor requirements [79].

6.1.5 Hyperspectral imaging sensors (HIS)

Hyperspectral imaging sensors have proven successful in detecting and distinguishing weeds, showcasing their effectiveness in agricultural applications. Hyperspectral imaging is commonly used for classifying agricultural systems and vegetation, being the most powerful and, currently, the sole method capable of robust and automated discrimination of individual plant species in the field [80]. In a study by Zhang et al., a hyperspectral imaging system was developed and coupled with a micro-spray heated oil application system for weed control in early-growth tomatoes. The authors reported that this approach accurately identified tomatoes, black nightshade, and pigweed at rates of 95, 94, and 99%, respectively. Importantly, this method remains robust even in the presence of visual occlusion of the leaf margin [81].

7. Conclusion

Weed infestation stands out a significant biotic factor contributing to a decline in global pulses production. Traditionally, herbicides have been used to mitigate or eliminate the impact of this interference. Selection pressure from herbicides has led to the emergence of herbicide-resistant weeds. Owing to this, herbicide exhibits dual effect as it not only eliminate weeds but also harm pulse crops. Therefore, the primary objective of plant breeding programs is to develop herbicide-resistant pulse crops with superior qualities. Induced mutation emerges as a highly efficient tool, widely utilized for quality improvement. Using physical or chemical mutagens, pulse crops can acquire resistance to herbicides. Consequently, this technique has found successful application in cereals, oilseeds, pulses, vegetables, and other crops. Seed mutagenesis is deemed an easy and cost-effective approach, and it requires substantial effort and time to produce desired crops. EMS, a chemical mutagen, is proving to be the most efficient choice for seed mutagenesis. Moreover, mutation breeding accompanied with modern technologies that help to identify the mutated alleles, leading to the development of successful mutants. This, in turn, helps to understand the gene function and enhance crop traits. New breeding technologies (NBTs) like genome editing enable targeted mutations in crop genomes, potentially increasing the transformation of herbicide tolerant crops. However, these methods have not yet been implemented in pulses. Therefore, researchers should consider integrating modern techniques alongside mutation breeding to develop herbicide-resistant pulse crops. In addition to induced mutation, researchers are also exploring alternative, precise, and chemical-free options such as thermal application, laser techniques, robotics, UVAs, and HIS for weed control in pulses.

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Edited by Muhammad Aamir Iqbal

Welcome to the edited volume *Weed Management - Global Strategies*, which presents a unique exploration of weed management strategies. This book aims to highlight the relevance of weeds in modern farming systems because they have emerged as nature's most persistent invaders, posing enormous challenges for researchers, farmers, gardeners, and environmentalists alike. This book illustrates the latest and most concentrated literature for mastering weed management by presenting a comprehensive guide to controlling weeds sustainably. Whether you are a professional agronomist, a backyard gardener, or a student of environmental science, this book offers fundamental and advanced knowledge to identify and understand common weed species, implement integrated (cultural, mechanical, biological, and chemical control) weed management strategies to minimize herbicide dependency with sustainable alternatives. The book presents strategies for improving crop yields and preserving ecosystem health. The book is packed with useful, practical tips, detailed case studies, and clear illustrations, which are bound to assist in mastering weed management and empowering the readers to take control of their landscape and protect their long-term productivity. Moreover, this edited volume will assist the audience in discovering the science, art, and sustainability of effective weed control because every great harvest begins with a well-managed field. Dr. Muhammad Aamir Iqbal (Editor of the book) is a renowned researcher with over a dozen years of experience in the agronomy of field crops and has dedicatedly worked to compile this book for a broader audience. After going through the challenges and eco-biologically viable strategies for weed management documented throughout the pages of the book, the audience must consider their role in reducing the use of herbicides to promote environmental health and ecosystem sustainability. This book is bound to serve as an invitation to all stakeholders (researchers, environmentalists, policymakers, students, and chemical engineers) who are passionate about the sustainable management of indigenous and invasive weeds.

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