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# EXPLORING NON-CHEMICAL METHODS FOR SUSTAINABLE WEED MANAGEMENT

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## ABSTRACT

This paper explores the significant challenges posed by weeds, which severely reduce crop yields and threaten global food security. Weeds compete with crops for vital resources and contribute to decreased food quality and production. The study emphasizes the importance of non-chemical weed control methods, particularly bioherbicides, as environmentally friendly alternatives. Additionally, it examines the role of robotics in weed management, focusing on the integration of artificial intelligence (AI) to enhance precision and efficiency. The application of laser technology in weed control is also discussed as a non-invasive and targeted approach. Furthermore, the paper investigates the allelopathic effects of plant extracts on weeds, particularly the generation of reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, and hydroxyl radicals. These ROS induce oxidative stress, leading to damage in cellular components like DNA, proteins, and membranes, and eventually triggering cell death and necrosis. The paper highlights the potential of plant-based solutions in sustainable weed management, contributing to eco-friendly agricultural practices. Additionally, the study underscores the importance of non-chemical weed control for minor crops, which contribute over €60 billion annually to the EU agricultural sector. Due to limited herbicide availability, integrated non-chemical strategies are vital, with approaches varying based on factors like cultivation system, market type, and expertise. These methods are essential for sustainable production and food security.

**Keywords:** weed, non-chemical methods, bioherbicides, allelopathic compounds.

## 1. INTRODUCTION

The global population is growing rapidly, with estimates predicting it will reach 9 billion by 2050. To accommodate this growth, agricultural production needs to rise by about 70% [1]. To satisfy

  

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the expected food demand by 2050, an extra 0.2 to 1 billion hectares of agricultural land could be needed [2].

Around 3,000 plant species generate approximately 400,000 tons of herbal material annually, which is traded globally. China and India are the leading producers and exporters of herbal plants [3]. Global agricultural herbicide usage is projected to see a modest rise, from approximately 2.3 million metric tons in 2023 to around 2.4 million metric tons by 2027 [4].

The herbicide market has experienced significant growth in recent years. It is expected to increase from $47.38 billion in 2024 to $54.42 billion in 2025, reflecting a compound annual growth rate (CAGR) of 14.9% [5]. The bioherbicides market is projected to reach approximately $2 billion by 2025, following a compound annual growth rate (CAGR) of 11% from 2020 to 2025 [6].

Weeds represent a major challenge to global agricultural productivity, with potential crop yield losses attributed to weeds estimated at 43% worldwide. Weeds compete with crops for vital resources such as nutrients, water, and light, and can also act as hosts for pathogens, leading to diseases that impact crop growth, yield, and overall management.

Weeds are highly efficient colonizers, exhibiting rapid reproduction rates and the production of a large quantity of small seeds with exceptional longevity in the soil. These seeds are capable of remaining viable for extended periods, enabling weeds to persist in even the most challenging environmental conditions, thereby contributing to the establishment of a long-term soil seedbank.

Weeds have a substantial economic impact, contributing to lower crop yields, higher production costs, and diminished crop quality. As a result, effective weed management is crucial for maintaining crop productivity and profitability.

In minor crops, the limited availability or complete absence of herbicides necessitates the adoption of integrated non-chemical weed control strategies. Minor crops primarily encompass vegetables, fruits, seed crops, herbs, medicinal plants, and spices. These crops contribute over €60 billion annually to the European Union's agricultural production, representing more than 20% of the total agricultural value. The sustainable production of minor crops is crucial for both public health and national economies, as it enhances agricultural productivity and ensures a diverse, nutritious food supply, thereby supporting food security. Weed control methods vary based on technical and economic factors, such as the cultivation system (open field or greenhouse), sowing or transplanting schedules, market type (e.g., fresh market, conservation, processing, or seed industries), and the level of expertise. As a result, non-chemical weed control approaches can differ significantly, reflecting the unique characteristics of each minor crop [7].

  

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In the European Union, a minor crop is characterized by cultivation on an area between 600 and 10,000 hectares, with annual production not exceeding 200,000 tons, and a daily dietary contribution ranging from 1.5 to 7.5 grams [8]. Effective weed control in minor crops demands the integration of various strategies, including agronomic, cultural, physical, mechanical, and chemical methods, all working together within an Integrated Weed Management System (IWMS).

The objective of this paper is to explore alternative non-chemical approaches for weed management, with a particular focus on bioherbicides. This study aims to contribute to the reduction of herbicide usage, given their detrimental effects on both the environment and human and animal health.

## 2. WEED CONTROL METHODS

In recent decades, various weed management techniques have been employed. These include physical methods, such as manual weed removal; cultural practices like crop rotation, cover cropping, and intercropping; thermal methods that use heat from fire, flames, or hot water to eliminate weeds; biological methods involving natural predators for weed control; mechanical control through the use of farm machinery; chemical control via herbicide application; laser weeding technology; and integrated weed management strategies. However, the most widely used weed control methods remain mechanical and chemical approaches.

There are currently two main approaches to weed control in agriculture: the traditional method, which relies heavily on synthetic herbicides, and the modern approach, which focuses on mechanical techniques, precision agriculture, and sensor-based strategies. Traditional weed control involves manual labor, cultural practices, and herbicide use, while modern strategies integrate these methods with advanced technologies like remote sensing, robotics, and precision farming techniques [9]. The choice between these methods depends on factors such as environmental considerations, crop types, and local agricultural practices.

### 2.1 Chemical weed control

Chemical weeding involves the application of herbicides to control weeds in agricultural fields. Herbicides either kill or inhibit weed growth, playing a crucial role in modern agriculture by ensuring high-quality crop production and minimizing yield losses caused by weeds and plant diseases. The use of herbicides has reduced the need for extensive manual labor, as they replaced hand-held mechanical tools, leading to lower production costs.

In the U.S. agricultural sector, herbicides represent 60% of the total volume and 65% of the expenditures on all pesticides used by farmers [10]. While herbicides offer significant advantages in terms of effective weed control and enhanced crop productivity, their widespread and often unregulated use can lead to serious ecological repercussions and increase the risk of chemical residues entering the human food chain through contaminated food and water, posing potential health risks.

Therefore, it is essential to reduce agriculture's reliance on agrochemicals and traditional field spraying methods for weed control. This can be achieved through selective or spot spraying systems, where the nozzle is activated or deactivated based on weed detection, nozzle positioning, and control system decisions. Herbicide spraying can be implemented in two primary ways: prescription map-based spraying and real-time sensor-based spraying.

Prescription map-based herbicide spraying involves creating a field weed map using various sensor technologies and combining herbicide application details (such as dose and flow rate) with location data to generate a prescription map. This map aids in decision-making for herbicide spraying systems. Additional data, like soil type, field topography, organic matter, and field history, can be integrated to enhance the system's accuracy and adaptability to varying environmental conditions. Weed location data can be gathered manually or through remote sensing technologies. Manual sampling is impractical for large fields due to its cost and time requirements. In contrast, remote sensing methods, such as satellite or drone imagery, offer a more efficient and timely approach. For instance, multispectral images captured by drones have been used to create prescription maps for variable herbicide applications based on canopy maps [11]. Additionally, on-vehicle sensor technologies, including GPS and cameras, can collect data on weed location, species, and density.

**2.1.1 Real-time sensor-based spraying systems** operate independently of external data sources and do not require weed or prescription maps. These systems typically include an imaging unit that captures high-resolution images of the agricultural field in real time. Image processing algorithms, utilizing techniques like feature extraction, segmentation, and classification, are then applied to differentiate weed plants from crops and the surrounding environment. When the system identifies weeds, it sends a control signal to activate the spraying unit.

Hyperspectral imaging (HSI) captures more than 100 images across a broad range of wavelengths in the electromagnetic spectrum, whereas traditional imaging methods, such as RGB and multispectral, typically record only three to ten channels or bands within the visible spectrum. Hyperspectral remote sensors are gaining recognition as a valuable tool for weed detection in field crops. These sensors capture high-resolution images with both spatial and spectral precision, making them particularly effective for the early identification of weeds. Hyperspectral weed identification leverages the distinct spectral reflectance of plants to distinguish between weed and crop species. This unique reflectance is due to the specific chemical composition within plant cells, such as chlorophyll content and water absorption, which vary across different plant species. These chemical properties influence how plants interact with light, whether from natural sunlight or

  

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artificial sources, contributing to their reflective characteristics. Studies have employed portable hyperspectral sensors mounted on ground-based platforms to capture high-resolution data. Furthermore, the growing use of cost-effective unmanned aerial vehicles (UAVs), like drones, and unmanned ground robots has significantly expanded the use of HSI for weed identification, offering new opportunities for precise and timely data collection in precision agriculture [12].

Unmanned aerial vehicles (UAVs) offer precise and useful data regarding crop health, weed detection, disease identification, and pest control, providing essential insights for agricultural management. However, challenges persist in areas such as data handling, algorithmic complexity, and operational limitations under varying environmental conditions. This paper explores potential solutions to these issues and highlights areas for future research aimed at enhancing UAV-based agricultural operations [13].

The rise of herbicide-resistant weeds is diminishing crop productivity, highlighting the need for new, environmentally sustainable methods to manage weeds. The growing interest in organic farming encourages the use of alternative weed control techniques that exclude chemical herbicides, thereby reducing the risk of herbicide-resistant weed development.

### 2.2 Non-chemical weed control

Non-chemical weed control involves eliminating weeds without the use of harmful chemicals. Often known as cultural or organic weed management, this approach includes techniques such as hoeing, hand-pulling, using hot water, or utilizing methods like foamstream. Foamstream is a herbicide-free weed control technique that avoids the use of potentially harmful chemicals, such as glyphosate. Instead, it employs a biodegradable foam combined with near-boiling water, which is applied to the weed. The foam acts as an insulator, keeping the water at a high temperature (57°C and above) for a longer duration compared to other weed control methods. The heat damages the plant's cell structure, leading to the death of the weed [14].

Non-chemical weed management in medical and aromatic plant cultivation is essential for maintaining the purity and quality of these sensitive crops (Figure 1). Several non-chemical methods can be employed to manage weeds in such fields, including:

*Mulching*

The application of organic or synthetic mulch around plants effectively suppresses weed growth by blocking sunlight, reducing seed germination, and conserving soil moisture.

Mulch is a key agricultural practice that involves covering the soil surface to conserve water, reduce erosion, and prevent surface runoff. It improves soil conditions by increasing temperature,

  

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fertility, and microbial activity, leading to better seed germination, root growth, and plant development, which boosts crop yields in areas with low water availability. Additionally, mulching enhances soil enzyme activity, supports plant metabolism, suppresses weed growth, and reduces weed biomass. Organic mulches, such as straw, wood chips, or grass clippings, further contribute to soil health through decomposition, enhancing nutrient availability. Using both organic and inorganic mulches on the soil surface effectively reduces evaporation, enhances moisture retention, and moderates soil temperature. Additionally, mulch helps prevent soil erosion, suppresses weed growth, and positively impacts the physico-chemical and biological properties of the soil [15].

*Mechanical Weeding*

Mechanical weed control involves the use of tools such as hoes, weeders, or mechanical cultivators to physically remove or disturb weeds from the soil. This method is particularly effective for shallow-rooted weed species and can be carried out manually or with tractor-driven equipment, depending on the scale of the operation.

*Mechanical weeding*

Mechanical weeding involves controlling weed growth through techniques such as cutting, plucking, burning, burying, or pressing with various tools or machines. These tools range from simple handheld devices to larger, machine-driven equipment. Popular mechanical weeding methods include hoes, harrows, tractor hoes, mowing, cutting, and steaming. Mechanical weeding is considered more environmentally friendly as it avoids the use of chemicals. However, it tends to be slower than chemical methods and may inadvertently damage nearby crops, which can lead to reduced crop yield and lower profitability for farmers.

*Flame Weeding*

Flame weeding utilizes a torch to apply heat directly to weeds, causing cellular damage and inhibiting further growth. This method is particularly effective for controlling small, young weeds and can be employed without the use of chemicals. However, it must be applied with caution to avoid unintended damage to the crops.

*Solarization*

This technique involves covering the soil with clear plastic sheets during the peak of the growing season to trap solar radiation and elevate soil temperatures to levels lethal to weed seeds and seedlings. In addition to weed control, solarization can also reduce soil-borne pathogens, enhancing overall soil health.

*Cover Cropping*:

  

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The practice of growing specific crops, such as legumes or grasses, between rows of medical and aromatic plants can help outcompete weeds. These cover crops provide soil shading, suppressing weed seed germination, and simultaneously improve soil structure and fertility by enhancing organic matter content.

*Hand Weeding*

Despite being labor-intensive, hand weeding remains one of the most effective non-chemical approaches for controlling weeds, particularly in small-scale or high-value medical and aromatic plant production. Hand weeding minimizes soil disturbance, thus maintaining soil integrity and plant health.

*Crop Rotation*

Rotating different plant species each growing season disrupts weed life cycles, as different crops compete with different weed species. This practice reduces the weed seed bank in the soil and enhances overall field productivity, promoting sustainable weed management.

*Biological Control*

Biological control involves introducing natural weed competitors or predators, such as specific insects, fungi, or nematodes, that target and suppress weed populations. This approach can be particularly useful for managing specific weed species in a controlled manner.

*Grass and Weed Barriers*

Physical barriers, such as landscape fabric or plastic mats, can be installed around plant roots to prevent weed growth. This method is particularly effective in high-value crops, where precision and minimal disturbance are necessary to maintain crop integrity.

By adopting these non-chemical strategies, growers can effectively manage weeds while preserving the quality and medicinal properties of aromatic and medicinal plants, ensuring a more sustainable approach to cultivation.

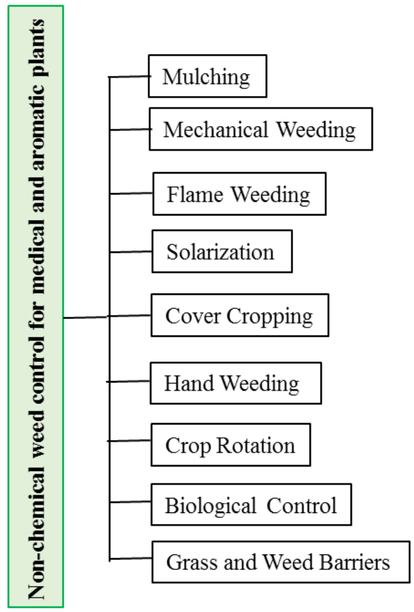


**Figure 1: Non-chemical weed control for medical and aromatic plants**

*Precision farming*

Precision farming employs advanced sensors and control systems, helps with tasks such as weed identification within crops, allowing for better understanding of their effects on nutrient absorption and yield quality [16].

*Agricultural robots and automated equipment*

Agricultural robots and automated equipment are mobile machines that can handle repetitive, time-consuming farming activities like weeding, plowing, planting, and harvesting with great efficiency. These robotic technologies are intended to reduce dependence on human labor, thereby addressing the challenges posed by labor shortages in the agricultural sector.

### 2.3 Robotic weed control

Robotic weed control utilizing sensors and machine learning (ML) or deep learning (DL) algorithms for weed identification has transformed precision weed management.

Machine learning and deep learning, as branches of AI, have significantly advanced object detection and classification in images and videos. These technologies are essential in shifting from traditional to precision agriculture, especially in weed management. What once depended on manual labor is now enhanced by smart devices that improve weed detection efficiency. Despite these advancements, challenges remain in weed detection, such as the visual resemblance between

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weeds and crops, issues with occlusion and lighting, and the necessity for early-stage weed control [17]. Deep learning outperformed machine learning in terms of accuracy across various conditions. While machine learning required careful feature selection to achieve high classification accuracy, particularly in challenging scenarios like lighting variations and early plant growth stages, deep learning provided superior performance. Additionally, machine learning necessitated a precise segmentation process, especially in cases of occlusion. On the other hand, machine learning's advantage was its ability to process in real time, as it used smaller models that didn't require additional *graphics processing units (*GPUs). However, with the rapid advancements in GPU technology, deep learning has become more prevalent for precise weed identification due to its greater accuracy.

Traditional image processing and ML algorithms have been applied to digital images, yielding promising results in weed identification and classification. However, ML techniques often require extensive domain expertise in feature engineering to extract relevant shape, color, and texture data for different weed and crop species. Furthermore, the performance of ML models can be affected by data variability, including variations in image acquisition methods and environmental factors such as occlusion, overlapping, and lighting conditions. In contrast, deep learning (DL) models offer automated feature extraction and adaptive learning capabilities, enabling more accurate object detection and classification from raw data. DL has demonstrated success in precise weed detection and localization, facilitating real-time weed control and advancing site-specific weed management (SSWM). SSWM can be enhanced by using advanced sensors and variable rate technology (VRT) to apply targeted weed control strategies.

### 2.3.1 Integration of AI techniques and robotics

Agricultural machinery integrated with advanced robotics and artificial intelligence (AI) has widespread applications in tasks such as seeding, crop disease detection, plant phenotyping, harvesting, and weeding. Weeding robots, in particular, offer the potential to implement intelligent weed management strategies, enhancing both efficiency and crop quality. This potential has sparked growing interest in utilizing robotics and AI to accurately detect and control weeds. The key components of a weeding robot include autonomous navigation, precise weed identification, mapping, and weed control techniques, with the identification of weeds being the most complex and challenging task.

To mitigate the environmental impact of extensive herbicide use while addressing food security challenges, the integration of AI techniques and robotics can be employed to manage agricultural chemical applications in a more sustainable manner. The transition to utilizing robotics for sustainable weed management has the potential to reduce herbicide usage, fostering a more environmentally sustainable agricultural production system. For example, a drop-on-demand

  

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(DoD) system, which sprays 5.3 µg of glyphosate per droplet, effectively controlled all weeds in a carrot field [18].

Similarly, a robotic platform with a specialized end effector for direct chemical application achieved a remarkable success rate, eliminating about 90% of the targeted weeds. Notably, this method used only 22% of the active ingredients compared to traditional broadcast application [19]. Future weed management systems should prioritize targeted chemical application, as this approach can address the challenges of chemical weeding and contribute to more effective weed control strategies. Smart sprayer systems, which incorporate sensors for navigation and real-time weed-crop classification, have also been utilized to reduce herbicide use [20].

Agricultural robots typically incorporate advanced technologies such as autonomous navigation, data mapping, automatic control systems, machine vision, and image processing (Figure 2).

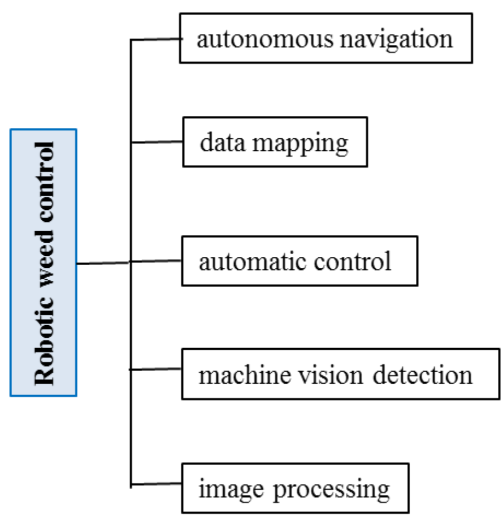


**Figure 2: Robotic weed control**

Autonomous navigation refers to a robot's capacity to accurately identify its location, plan the most efficient route, and navigate without collisions.

The autonomous navigation of agricultural robots depends on the effectiveness of sensors that gather real-time data about the robot's position, field conditions, and obstacles. Advanced control algorithms process this data to generate detailed field maps, plan optimal paths, and make real-time adjustments to the robot's movement to avoid collisions with obstacles.

Among the various sensors employed for autonomous guidance in agricultural fields, global positioning systems (GPS) and machine vision-based navigation are the most commonly used methods. GPS is a widely utilized technology for lateral guidance in agricultural robotics, offering

  

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precise positioning capabilities for navigation during various field operations, including planting, weeding, and harvesting. However, the accuracy of GPS positioning can be compromised by factors such as obstructions, radio frequency interference, multipath errors, satellite geometry, and atmospheric conditions. For accurate operation, the GPS base station should be positioned within about 10 km of the mobile GPS, which is responsible for controlling the steering of the agricultural robot [21].

Mechanical weeding typically involves the removal of weeds in agricultural fields through methods such as plucking, burning, or cutting. When integrated with various sensors, including laser, ultrasonic sensors, imaging technology, and automatic guidance systems, mechanical weeding systems have the potential to significantly enhance weed management effectiveness. Achieving high weeding accuracy requires consideration of factors such as treatment timing, frequency, type of cultivator, and intensity. The incorporation of sensor technology into tractor-driven machinery has notably improved the precision of mechanical weeding, enabling effective weed control within a narrow margin (~5 cm) of plant rows [22].

Figure 3 illustrates the key milestones and technological advancements in weed management, showcasing the transition from traditional practices to technology-driven approaches in agricultural fields.

  

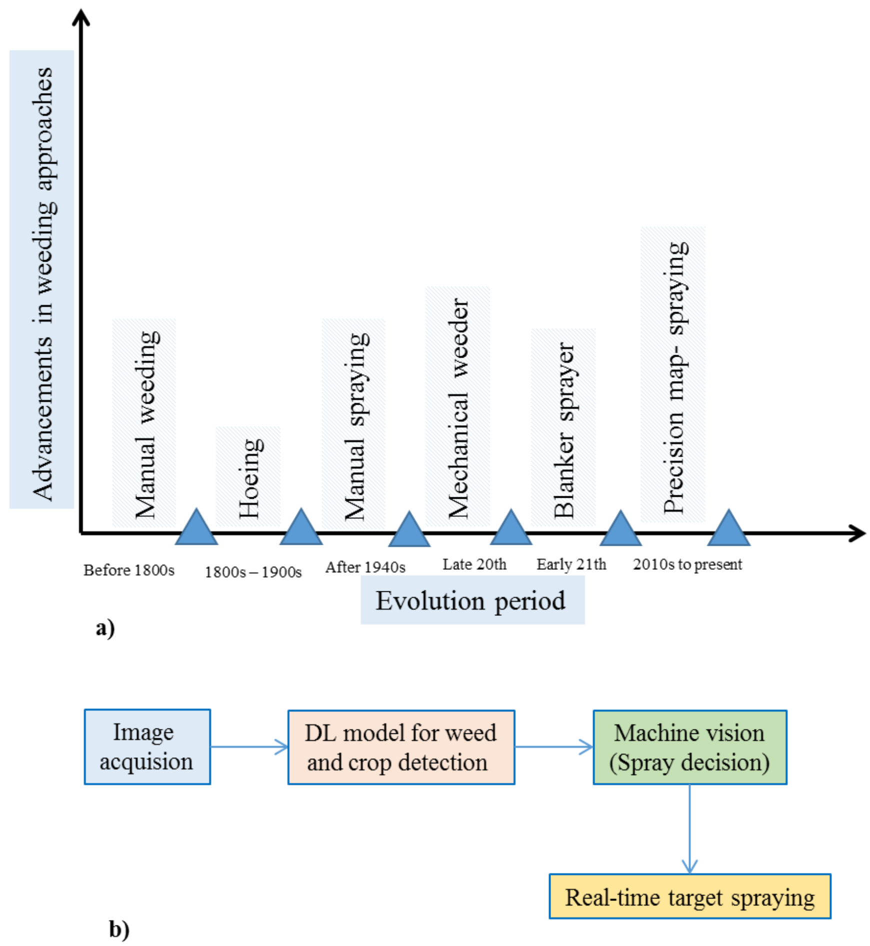


**Figure 3: Weed management strategies: (a) The progression of weed control methods from manual removal to advanced robotic weeding, (b) Current research developments and the future potential of using deep learning techniques for real-time, site-specific weed management.**

### 2.3.2 Commercial Robots for Precision Weed Management

Over the past few decades, various promising technologies for weed management have been developed and integrated into commercial agricultural robots. However, field-based weeding robots still face challenges related to vision systems, robotic actuation, and navigation in semi-structured agricultural environments, necessitating further research and innovation to develop fully autonomous platforms. Despite these challenges, several robotic weed management systems show significant potential for future weed control.

  

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One such example is the RIPPA-Robot for Intelligent Perception and Precision Application, a joystick-controlled platform developed by the University of Sydney. This robot uses an intelligent sprayer system, VIIPA (Variable Injection Intelligent Precision Applicator), to precisely apply herbicides at high speeds, minimizing chemical use [23]. Similarly, the Asterix robot prototype, based on a drop-on-demand (DoD) system, achieves effective weed management with a tenfold reduction in herbicide use compared to conventional spraying methods [24].

Another notable platform is the AgBotII, developed by [25]. This modular, energy-efficient robotic system integrates a vision-based weed detection and classification system, mechanical weeding tools, and a precision spray unit. In field trials, it achieved 96% accuracy in plant classification and 92.3% accuracy in classifying individual weed species. A fully autonomous, solar-powered weeding robot, developed by Ecorobotix (2023) [26], uses machine learning for weed detection and micro-dosing of herbicides, reducing chemical use by more than 90%. The robot has a four-wheel drive system, offering high maneuverability and a short turning radius, and can treat up to 10 hectares per day.

Many intelligent mechanical weeders for precision weed management are now commercially available, such as the Tertill, the Autonomous Farm Robot Oz, and Robotti. Additionally, Verdant Robotics developed the Model B Smart Sprayer, capable of spraying 3.75 acres per hour with high precision, reducing chemical use by up to 96% for both conventional and organic farming. Laser-based weed management systems have also made significant strides, with a laser weeder capable of covering 2 acres per hour at 1 mile per hour, eliminating up to 200,000 weeds per hour with sub-millimeter accuracy.

These advancements mark a shift from traditional, labor-intensive weeding methods to more accurate, autonomous, and environmentally friendly approaches, representing a significant step toward sustainable weed management practices.

**2.4 Laser weeding technology** offers a promising alternative to chemical and mechanical weed control, supporting more sustainable weed management by reducing reliance on herbicides and soil tillage. While mechanical and chemical methods are effective, they have significant environmental drawbacks. Real-time laser weeding robots can mitigate the risks associated with traditional methods, enhancing crop productivity through precise weed targeting. The laser emits a high-intensity light beam that heats the water molecules inside weed cells, causing tissue damage. Recent advancements have seen autonomous laser weeding robots incorporating deep learning (DL) object detection models for accurate weed identification. These models help target weeds at their apical meristem, effectively eliminating them. For example, a $CO_2$ laser with a 10,600 nm wavelength successfully treated 90% of weeds with an energy consumption of 54 J per target [27].

  

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Chen et al. (2024) [28] explored the effectiveness of combining color feature techniques with Otsu's method (OTSU) for distinguishing weeds from cotton plants at different growth stages.

Ineffective weed management and the presence of weeds in cotton fields can lead to substantial declines in crop quality and yield, with potential losses of up to 90%. The results showed that the image segmentation method achieved a recognition rate of 74.1% at the second growth stage. During the third stage, weed identification mainly focused on lambsquarters (*Chenopodium album*). A significant finding was that the standard deviation (SD) differences between the red (R), green (G), and blue (B) components of plant images indicated that the SD difference between R and B was less than 5, which proved to be an effective threshold for identifying lambsquarters. The recognition rates for cotton and lambsquarters were 71.4% and 92.9%, respectively, with an overall recognition rate of 82.1%. These findings have practical implications for weed management, such as enabling targeted herbicide applications, reducing environmental impacts, and improving crop yields.

## 3. BIOLOGICAL WEED CONTROL

Biological weed control methods involve using living organisms to protect plants and are described as the use of an agent, a combination of agents, or biological processes to reduce weed growth. Biological weed control offers several advantages over other methods, including a lower risk of soil, water, and food contamination from herbicide residues.

### 3.1 Bioherbicides

Bioherbicides are natural products from phytopathogenic microorganisms or microbial compounds used for weed control. They reduce weed populations, creating better conditions for target crops. Plant extracts, allelochemicals, and certain microorganisms can inhibit weed germination and growth. Phytopathogenic fungi produce toxic substances and secondary metabolites that aid in weed control. Enzymes like cutinases, pectinases, cellulases, and others can break down plant cell walls, allowing pathogen entry and increasing disease severity. Using agro-industrial residues for fermentation produces bioherbicidal extracts, which are cost-effective alternatives to synthetic herbicides [29].

Bioherbicides use various mechanisms to control weeds, including microbial bioherbicides that infect, damage, or inhibit weed growth, and plant-derived bioherbicides that target specific biochemical processes. They can be applied through spraying, seed treatments, or soil incorporation. However, bioherbicide development faces challenges such as the diversity of weed species, lengthy and costly regulatory approvals, scaling production, and ensuring product stability. Despite these hurdles, bioherbicides offer benefits by reducing chemical herbicide reliance, minimizing environmental pollution, and supporting sustainable agriculture. Developing locally adapted bioherbicides and fostering collaboration among researchers, industries, and policymakers can enhance their adoption, while addressing knowledge gaps is crucial for their widespread use [30].

Bioherbicides used for weed control in agricultural systems can be developed from higher plants, microorganisms, or microbial phytotoxins. Bioherbicides cannot act as a substitute for synthetic herbicides, but they can be a complementary tool in weed control. The advantages of bioherbicides are: high level selectivity, low side effects on non-target organisms, and almost no residue problems.

The first registered bioherbicide was Devine, produced by a facultative fungus, *Phytophthora palmivora Butl*. [31]. Today, there are more than 200 plant pathogens as candidate bioherbicides. Despite the large number of studies on bioherbicides, the number of commercial preparations on the market is small due to limiting factors such as environment (temperature and humidity), biology (host diversity and resistance) and technology (formulation and mass production). The influence of bioherbicide and C/N ratio has a significant effect on fungal sporulation [32]. The formulation of bioherbicide is another factor that affects its activity because it is difficult to maintain a living organism to successfully reach target plants under field conditions. Many organisms do not perform well in vivo as shown by in vitro studies [33].

Orange peel, rich in sugars, pectin, and fibers, is a good substrate for producing bio-composites. Fermentation of orange peel with microorganisms can create valuable products, including acids and enzymes with biological effects for weed control. Shrimp shells, abundant in the fishing industry, are another source of bioactive polysaccharides like chitosan, which can enhance herbicide performance and influence soil interactions. Orange peel and shrimp shell residues provide substrates for enzyme production, with fermentation extracts showing activity in enzymes like pectinase, cellulase, and amylase. These low-cost alternatives have potential for weed control, demonstrated by their phytotoxic effects on *C. sativus*. Future studies should explore compounds that work synergistically with enzymes for more effective weed control. However, commercial application requires overcoming challenges in scheduling production and conducting field studies to prove efficacy under various environmental conditions [29].

Recently, the reaserch has shown that the phytochemicals present in plant extracts also play a crucial role in the plant-assisted synthesis of silver nanoparticles (AgNPs). These extracts are rich in molecules containing carboxyl, amino, carbonyl, hydroxyl, and phenol groups, which allow them to reduce metals like silver. Key phytochemicals involved in the bio-reduction process include aldehydes, ketones, flavones, sugars, terpenoids, carboxylic acids, and amides. Antioxidants, particularly flavonoids (such as flavonols and flavan-3-ols), phenolic acids (like benzoic, hydroxycinnamic, and ellagic acids), and anthocyanins, are strongly associated with the

  

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reduction and capping of these nanoparticles. Additionally, other plant metabolites, such as proteins and chlorophyll, contribute to the stabilization of the nanoparticles [34].

Putnam and Duke (1978) [35] were the pioneers in exploring the potential of using allelopathic crops for weed management in agriculture, aiming to reduce the significant environmental impacts associated with conventional methods.

It has long been established that certain plants possess the ability to suppress the growth of surrounding vegetation, a phenomenon attributed to compounds known as “allelochemicals”. Allelopathy is a biological phenomenon in which an organism produces one or more biomolecules that affect the growth, survival and/or reproduction of other organisms [36]. Allelochemicals, which include terpenoids, nitrogen-containing compounds, and phenolic compounds, are present in various parts of plants, such as leaves, stems, roots, rhizomes, seeds, flowers, and even pollen [37-38]. Unlike many synthetic agrochemicals, allelochemicals are biodegradable, predominantly water-soluble, and composed of non-halogenated molecules [39]. Allelopathic compounds can be used to develop a sustainable weed management system based on natural products.

This has led to significant interest in species from the Lamiaceae family, which represent 43% of the species reviewed in the literature, due to their high concentrations of volatile allelochemicals. Numerous studies have demonstrated that extracts from various Lamiaceae species can effectively inhibit the germination and growth of multiple weed species. Essential oils (EOs) derived from plants such as oregano, thyme, rosemary, sage, and mint have emerged as particularly potent bioherbicide candidates. The phytotoxic effects of these extracts, especially the EOs, are primarily ascribed to volatile bioactive compounds, including α-pinene, limonene, 1,8-cineole, carvacrol, camphor, and thymol, each of which exhibits varying degrees of phytotoxicity [40].

The allelopathic influence of plant extracts on weeds increases the levels of reactive oxygen species (ROS) such as superoxide ($O_2^-$), hydrogen peroxide ($H_2O_2$), and hydroxyl radicals, leading to damage in cellular components like DNA, proteins, and membranes. This oxidative stress causes electrolyte leakage, activates enzymes like endonucleases and proteases, and triggers programmed cell death, ultimately inhibiting weed growth and inducing necrosis. The abnormal peroxidation of lipids and dysfunction of ROS scavenging enzymes such as catalase (CAT), peroxidase (POX), and superoxide dismutase (SOD) suggest the toxic effects of plant extracts. Under normal conditions, CAT and POX help detoxify $H_2O_2$, while SOD scavenges $O_2^-$ to reduce oxidative damage. However, the application of plant extracts increases CAT and POX activity while suppressing SOD, leading to an accumulation of $H_2O_2$ that the weeds cannot control. Furthermore, the phenolic compounds in the extracts hinder cell division and slow down weed growth [41].

In certain plant species, essential oils have been observed to inhibit seed germination, induce toxicity, and disrupt photosynthetic activity. Ootani et al. (2017) conducted a study to evaluate the effects of essential oils and their primary component, citronellal, on the germination and growth of crabgrass (*Digitaria horizontalis*) and burrgrass (*Cenchrus echinatus*). Essential oils from *Eucalyptus citriodora* and *Cymbopogon nardus*, along with pure citronellal, were applied at concentrations of 1%, 10%, and 20% to assess seed germination and phytotoxic effects. The treatments were administered when the plants reached the four-leaf stage. The results revealed that seed germination was drastically reduced, with a 97-99% decrease compared to untreated controls. Citronellal caused more significant reductions in germination than the essential oils. Additionally, the phytotoxic effects on plant height and the dry mass of shoots and roots were evaluated. The oils produced negative effects within 12 hours of treatment, with the 20% concentration leading to a reduction in dry mass accumulation in shoots and roots. Although the number of tillers was not significantly impacted, stomatal opening in burrgrass was affected. Furthermore, the oils resulted in a reduction of more than 80% in chlorophyll content and over 90% in total protein content in the weeds. These findings suggest that essential oils, particularly citronellal, could have potential as bioherbicides for weed control [42].

Table 1 presents recently developed bioherbicides and their associated activity.

**Table 1: Bioherbicidal activity of plant extracts, olive vegetation water, and fungi isolated from plants.**

| Extract | Weeds | Bioherbicidal activity | Ref. |
|---|---|---|---|
| Leaf aq. extracts (40 and 80%) obtained from Cynara cardunculus L. plant species | Amaranthus retroflexus L., Diplotaxis erucoides (L.) DC., Portulaca oleracea L., Lavatera arborea L., Brassica campestris L. Solanum nigrum L. | Reduction of seed germination compared to the control for<br>A. retroflexus (-58.1%),<br>D. erucoides (-43.9%),<br>P. oleracea (-42.5%) | [43] |
| Leaf needle extracts chir pine (*Pinus roxburghii*) | *Melilotus albus* and *Asphodelus tenuifolius* | Methanolic extract, at 100% concentration, exhibited the highest weed seed germination inhibition (74% for *M. albus* and 65% for *A. tenuifolius*), followed by the ethanolic extract (68% and 64%, respectively).<br>Alcoholic extracts possess stronger bio-pesticidal activity compared to aqueous extracts | [44] |

| | | | |
|---|---|---|---|
| Olive vegetation water (OVW) | redroot pigweed (*Amaranthus retroflexus*), little mallow (*Malva parviflora*), common purslane (*Portulaca oleracea*), common sowthistle (*Sonchus oleraceus*) | Redroot pigweed showed the greatest sensitivity to OVW, with germination dropping from 30% in the control to 1-4% across all OVW treatments (100%, 75%, 50%, and 25%). | [45] |
| Fungi isolated (*Fusarium oxysporum*, *Fusarium proliferatum*, and *Trichoderma koningiopsis)* from plants (*Urochloa plantaginea*, *Euphorbia heterophylla*, and *Bidens pilosa*) | (soybean and corn) and resistant weeds | *T. koningiopsis* exhibited the most substantial effect on *E. heterophylla* (Mexican fire plant), causing up to 60% foliar damage, without displaying phytotoxicity to corn. | [46] |
| EtOAc extract from *Mimosa pigra* leaves | *Echinochloa crus-galli* (barnyardgrass) | strong inhibitory effects on the germination and growth of *Echinochloa crus-galli* (barnyardgrass) | [47] |

Scavo et al. (2024) [43] evaluated the allelopathic potential of leaf aqueous extracts (40 and 80%) obtained from *Cynara cardunculus* L. plant species on seed germination and mean germination time of six common weeds in Mediterranean agroecosystems: *Amaranthus retroflexus* L., *Diplotaxis erucoides* (L.) DC., *Portulaca oleracea* L., *Lavatera arborea* L., *Brassica campestris* L. and *Solanum nigrum* L. Effects varied with the weed species and the concentrations of the extracts. On average, the aqueous leaf extracts significantly reduced the final percentage of seed germination compared to the control for *A. retroflexus* (-58.1%), *D. erucoides* (-43.9%) and *P. oleracea* (-42.5%). The rate of germination decreased with increasing extract concentration. In *C. cardunculus* L. var. *sylvestris* the autoallelopathic activity also was demonstrated. These results are very promising in order to produce a bioherbicide based on *C. cardunculus* allelochemicals.

Botanical pesticides have garnered considerable attention due to their eco-friendly and non-toxic properties.

Alam et al. (2022) investigated the potential of chir pine (*Pinus roxburghii*) leaf needle extracts, obtained through various solvents, for biocontrol applications. The needles were separately soaked in methanol, ethanol, hot, and cold water in a solvent-to-plant ratio of 5:1 for 7 days. Analysis of the extracts revealed that hot and cold-water extracts contained higher concentrations of organic acids, siloxanes, and amides, while methanolic and ethanolic extracts had elevated levels of alcohols, ketones, terpenes, and phenolic compounds. The biocontrol efficacy of these extracts was tested on two weed species (*Melilotus albus* and *Asphodelus tenuifolius*) and an insect pest (*Plutella xylostella*). The methanolic extract, particularly at 100% concentration, exhibited the highest weed seed germination inhibition (74% for *M. albus* and 65% for *A. tenuifolius*), followed by the ethanolic extract (68% and 64%, respectively). The results indicate that alcoholic extracts, particularly those rich in phenols and terpenes, possess stronger bio-pesticidal activity compared to aqueous extracts. Consequently, these alcoholic extracts demonstrate significant potential as novel and safe bio-pesticides for the management of both weeds and insect pests [44].

Tubeileh and Souikane (2020) [45] aimed to evaluate the effects of four olive vegetation water (OVW) dilution levels and three compost/pomace extracts on the seed germination of four weed species: redroot pigweed (*Amaranthus retroflexus*), little mallow (*Malva parviflora*), common purslane (*Portulaca oleracea*), and common sowthistle (*Sonchus oleraceus*). In the first experiment, OVW dilutions (100%, 75%, 50%, and 25%) and a tap water control were tested. In the second experiment, extracts were made from olive pomace, olive/dairy manure compost, and dairy manure compost. For each treatment, 100 seeds were placed in 10 Petri dishes, with 2 mL of each solution applied and incubated for 24 days. Redroot pigweed showed the greatest sensitivity to OVW, with germination dropping from 30% in the control to 1-4% across all OVW treatments. Common sowthistle experienced a 4-day germination delay with OVW100. OVW100 reduced germination in little mallow, while OVW75 appeared to break seed dormancy and slightly increased germination. For common purslane, higher OVW concentrations decreased germination in the first six days. Compost extracts had minimal effect on germination, with some initially inhibiting germination or promoting it later in little mallow. Overall, OVW can be used to control weeds or stimulate their germination for later control, potentially depleting the soil's weed seed bank.

Reichert Júnior et al. (2019) [46] studied various fungi isolated from plants exhibiting fungal disease symptoms to assess their potential as bioherbicides against weeds (*Urochloa plantaginea*, *Euphorbia heterophylla*, and *Bidens pilosa*). The fungi were identified using molecular techniques, and the enzymatic products generated during fungal fermentation, including cellulase, lipase, peroxidase, and amylase, were quantified. A selectivity assessment of the bioherbicides was conducted on crops (soybean and corn) and resistant weeds. Among the isolated fungi, *Fusarium oxysporum*, *Fusarium proliferatum*, and *Trichoderma koningiopsis* showed significant bioherbicidal potential. Notably, *T. koningiopsis* exhibited the most substantial effect on *E. heterophylla* (Mexican fire plant), causing up to 60% foliar damage, without displaying phytotoxicity to corn. This study suggests new avenues for weed control, particularly in corn crops, based on the bioherbicide selectivity observed.

Khang et al. 2023 [47] found that the ethyl acetate (EtOAc) extract from *Mimosa pigra* leaves exhibited strong inhibitory effects on the germination and growth of *Echinochloa crus-galli* (barnyardgrass), outperforming other extracts. From this extract, six potent growth inhibitors were isolated and identified: lupeol (C1, 13.2 mg), stigmastane-3,6-dione (C2, 14.7 mg), quercetin (C3, 20.2 mg), chrysoeriol (C4, 28 mg), methyl gallate (C5, 21.5 mg), and daucosterol (C6, 16.0 mg). Quercetin (C3) completely inhibited seedling emergence, shoot height, and root length of *E. crus-galli* at 1 mg/mL, with an $IC_{50}$ for shoot height of 0.56 mg/mL. This study also marks the first report of the allelopathic activity of lupeol, chrysoeriol, and daucosterol from *M. pigra* leaves. The findings suggest that quercetin could be developed as a bio-herbicide for controlling barnyard grass and other weeds, contributing to safer agricultural practices.

## 4. CONCLUSION

In conclusion, the adoption of robotic platforms and precision technologies, such as smart sprayers and AI-driven weed identification systems, marks a significant advancement in weed management. These innovations allow for targeted chemical application, significantly reducing herbicide use while maintaining high weed control efficiency. Despite challenges such as early-stage weed detection and the visual similarity between weeds and crops, the integration of machine learning and deep learning algorithms has the potential to revolutionize precision agriculture. Additionally, bioherbicides offer a promising alternative to chemical herbicides, providing an eco-friendly solution to weed control. Although there are hurdles in the development of bioherbicides, including regulatory barriers, scaling production, and ensuring product stability, their benefits in reducing environmental impact and supporting sustainable agriculture are clear. Plant pathogens and allelopathic compounds also hold promise as part of a broader, integrated approach to weed management, reducing the reliance on traditional chemical methods. As research progresses, overcoming these challenges will enhance the feasibility and commercial availability of bioherbicides, contributing to more sustainable agricultural practices and reducing the environmental footprint of crop production. The future of weed management lies in the combination of innovative technologies, eco-friendly solutions, and integrated strategies that promote long-term sustainability in agriculture.

## CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

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