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# Technological Advancement in Weed Management

**V. Santhosh**
Department of Agronomy, Faculty of Agriculture, Annamalai University, Tamil Nadu- 608 002, India
*Corresponding Author: santhoshvmsh2000@gmail.com

Weeds are notorious for their ability to significantly reduce crop yields, often causing more economic damage than insects, fungi, or other crop pests. To effectively manage these pesky plants, it is crucial to assess the extent of crop yield and economic losses caused by weeds in agriculture (Gharde *et al.*, 2018).

As the world population continues to grow, the demand for food production also increases to sustain an anticipated 9 billion people by 2050. In light of these challenges, we examine the latest technological and innovative advancements that may provide a solution for sustainable weed management (Alexandratos and Bruinsma, 2012). By thoroughly understanding the biology and ecology of weeds and combining modern and traditional weed management techniques, we can develop more robust and diverse weed management systems. This holistic approach can lead to more sustainable practices for integrated weed management and resistance management, surpassing the limitations of current technologies that are proving to be ineffective (Westwood *et al.*, 2017).

## Challenges in Weed Management

The challenges faced in Indian weed research are multi-faceted. They include the effective management of weeds on small farms, the limited availability of labour and mechanical tools, and insufficient information on weed biology and fluctuations in weed flora. Additionally, herbicide-resistant weeds pose a significant threat, and there is a lack of understanding regarding the impact of climate change on weed growth and control. It is essential to promote integrated weed management with the use of herbicides while ensuring their safe use to prevent adverse effects on human health and the environment. This approach can also help prevent the development of herbicide resistance and aid in the management of invasive alien weeds (Rao *et al.*, 2018).

Farmers must possess a comprehensive knowledge of weeds, including their biology and how their populations respond to changes in crop management and climate. This presents a significant challenge for weed scientists to develop effective weed management strategies that take into account the impact of climate change on weed biology. (Kathiresan and Gualbert, 2016). Rao *et al.*, (2018) suggest a comprehensive weed management program for small farmers in India, involving robust cultivars, appropriate agronomy, land management, application technology, and herbicide rotation.

## Nanotechnology

Nanomaterial, according to the European Commission (EC) recommendation, is any material consisting of particles in an unbound state or in the form of aggregate or agglomerate, where at least 50% of the particles' number and size distribution lie within 1-100 nm range (Neme *et al.*, 2021).

Numerous techniques are utilized in the creation of nanoparticles, typically classified into two distinct categories as per the Royal Society and Royal Academy of Engineering. These categories include the top-down approach, which emphasizes the reduction of bulk material size, and the bottom-up approach, where materials are synthesized from the atomic level.

## Nano-encapsulation

Nanoencapsulation is a method that involves enclosing solid, liquid, or gas nanoparticles (referred to as the "core" or "active") in a secondary substance (known as the "matrix" or "shell") to create nano capsules. The technique enables multiple substances to be simultaneously applied while preventing interactions between them until they are released. According to a study by *Korres et al.*, (2019), nanoencapsulation has the potential to offer significant benefits.

According to research conducted by Sousa *et al.*, (2018), using PCL nano capsules containing atrazine showed promising results in effectively controlling *Amaranthus viri* and *B. pilosa* after they had emerged. This suggests that nano formulations could be a viable alternative for weed control.

In a study conducted by Sousa and colleagues (2018), the effectiveness of nano atrazine as a post-emergence herbicide against *Alternanthera tenella* plants was examined and compared with its impact on other types of weeds.

**Nano-carrier**

Herbicide nanocarrier research aims to reduce the non-target toxicity of herbicides and minimize their environmental impact. Some of the materials used in nanocarriers include chitosan, tri-polyphosphate, alginate, poly-ε-caprolactone, starch, and rice husk.

According to Grillo *et al.,* (2014), the combination of chitosan and paraquat herbicide had a lower risk of harming crops. Meanwhile, Abigail *et al.,* (2016) found that 2,4-D rice husk biochar (DrBC) can reduce herbicide leaching and release over a long period. In another study, Xiang *et al.,* (2018) observed that calcium carbonate with Prometryn was 20% more effective in suppressing *Cynodon dactylon*. In a recent study by Khan and colleagues (2022), the impact of nanoparticles of clodinofop propargyl and fenoxaprop-p-ethyl on weed control, growth, and yield of wheat (*Triticum aestivum L.*) was investigated through synthesis, characterization, and evaluation experiments.

**Nano emulsions**

Nano-emulsions refer to emulsions that are reduced to nanoscale size and are utilized to enhance the administration of active herbicidal substances. They are isotropic systems that are thermodynamically stable, wherein an emulsifying agent, such as a surfactant or co-surfactant, is employed to merge two immiscible liquids into a unified phase. Normally, nano-emulsion droplets are approximately 20-200 nm in size.

According to Kumar *et al.,* (2016), the combination of pretilachlor microemulsion (ME) and monolithic dispersion (MD) in nano-emulsion form was more effective in controlling *Echinochloa crus-galli* compared to the formulation that is available commercially. Hazrati *et al.,* (2017) found that a nano emulsion of *Satureja hortensis L.* essential oil at 1000 ìL/L inhibited the growth of *Amaranthus retroflexus.* Somala *et al.,* (2022) also tested the use of a Citronella essential oil-based nano emulsion as a natural post-emergence herbicide.

**Nano-biosensors**

A new technique for detecting herbicides, specifically the enzyme-inhibiting herbicide Metsulfuron-methyl, in soil has been developed using a nano-biosensor based on atomic force microscopy. This was reported by Da Silva and colleagues in 2013. According to Duhan *et al.,* (2017), the use of nanosensors in precision agriculture has improved the accuracy of herbicide release and control. As a result, herbicides have become more effective and environmentally friendly.

**Precision Weed Management**

Precision weed management (PWM) is a comprehensive approach that aims to increase farm productivity. This involves using a range of methods, such as need-specific, site-specific, and cost-effective weed sensing systems (both ground-based and aerial-based), and integrated weed management techniques that include chemical, mechanical, manual, and cultural methods (Rao, 2021).

**Artificial intelligence**

Convolutional neural networks (CNNs) were first implemented by LeCun *et al.,* in 1989 and have proven to be a precise tool for weed classification and object detection. While the adoption of CNNs is relatively recent, they have mostly replaced previous methods of AI for weed identification, as noted by Kamilaris & Prenafeta-Boldú in 2018.

Implementing site-specific weed management strategies can significantly reduce the usage of pesticides and promote biodiversity in agriculture. These goals can be achieved without affecting crop yields or incurring additional costs for subsequent weed control. Notably, various software programs, such as those developed by Gerhards *et al.,* (2022), can aid in detecting and managing weeds effectively.

In a study by Partel and colleagues (2019), researchers explored a cost-effective and intelligent approach to weed management using artificial intelligence. They created a smart sprayer that employed machine vision and AI to differentiate between target weeds and non-target items (such as vegetable crops) and accurately apply the spray to the intended location.

**Unmanned aerial vehicle**

Unmanned Aerial Vehicles (UAVs) are frequently used in precision agriculture. By combining image acquisition by drones and further processing by machine learning techniques, it is possible to identify weed patches in a cultivated field (Esposito *et al.*, 2021). The different types of sensors available as payloads are mainly categorized into three classes based on their ability to record spectral length and number. These classes include RGB (Red, Green, Blue) or VIS (Visible) sensors, multispectral sensors, and hyperspectral sensors.

In a study conducted by Hiremath *et al.*, (2023), the comparative effectiveness and work efficiency of Knapsack, Boom, and Drone Sprayers for weed management in Soybean (Glycine max L.) were evaluated as the primary objective.

**Robotics**

The synergy of computer vision, traditional machine learning, and deep learning has been instrumental in advancing weed detection and robotic approaches to mechanical weeding. As a result, autonomous weeding robots have rapidly emerged, integrating perception, decision-making, and control technologies to effectively reduce the environmental impact of pesticide use while saving labour (Zang *et al.*, 2022). The crucial initial phase of developing a smart and sustainable weeding management (SSWM) solution lies in detecting and recognizing weeds. Weed detection methods can be broadly classified into two categories: machine learning (ML) and deep learning (DL).

**Mechanical Methods**

**Abrasive grit method**

Innovative weed management techniques like abrasive weeding hold immense promise in curbing the need for extensive hand-weeding and tillage in organic farming. Organic agriculture relies heavily on non-chemical weed control methods, which are crucial in tackling herbicide-resistant weeds. However, the lack of effective non-chemical weed control measures is a cause for concern. To reduce reliance on broad-spectrum herbicides, it is imperative to develop new weed management strategies that incorporate diverse tools and techniques, as emphasized by Perez-Riuz *et al.*, (2018).

In a 2018 study conducted by Perez-Riuz *et al.*, various agricultural residues were tested as effective abrasive tools for weed control. The study examined the efficacy of abrasive grits derived from eight different agricultural sources (almond shell, grape seed, maize cob, olive seed, poultry manure, sand, soybean meal, and walnut shell) when delivered at high air pressures. The grits were evaluated in laboratory trials on common weeds found in tomato, sugar beet, and olive crops, *including Amaranthus retroflexus L., Chenopodium murale L., and Centaurea cyanus L.* The study also estimated application rates and costs of using agricultural residues. Results showed that the control of two- to three-leaf stage weed seedlings ranged from 30 to 100%.

In a study by Erazo-Barradas *et al.*, (2017), propelled abrasive grit was tested as a method for managing weeds in transitional corn grain production. It was found that the timing of grit application is crucial, much like that of herbicides. The results showed a significant decrease in in-row weed densities by approximately 60% and a reduction in biomass of up to 95%.

**Harvest weed seed control (HWSC):**

HWSC, an alternative weed control treatment, helps target the seed production of mature weed species in Australian grain systems. However, the viability of seeds in the soil seed bank determines the length of time BMP should be used to reduce the seed bank and prevent herbicide-resistant seed emergence (Norsworthy *et al.*, 2012).

Although annual management practices can impact the weed species above ground, the soil seed bank tends to respond at a slower pace due to the constant influx of weed seeds from multiple seasons of escaped weeds (Schwartz *et al.*, 2016). Farmers must decrease the amount of weed seeds in the soil seed bank in order to reduce the weed population they will have to handle in the future.

The narrow windrow burning system is an incredibly effective and straightforward HWSC technique. By utilizing a chute that's affixed to the back of the combine, the system efficiently gathers all the chaff together into one narrow row. Studies have demonstrated that this cost-effective method can decrease escaped Palmer amaranth by an impressive 73 per cent and reduce soil seed bank by 62 per cent over three years (Norsworthy *et al.*, 2016).

The chaff cart approach involves a mechanism for gathering and transporting chaff, which is connected to a grain harvester that deposits the weed seed into a bin designed for bulk collection. This technique enables the efficient collection and elimination of both chaff and weed seeds from the field (Schwartz *et al.*, 2015).

In 2005, Ray Harrington, a crop producer from Australia, developed the Harrington Seed Destructor (HSD). This innovative solution is a trailer-mounted cage mill equipped with chaff transfer systems. According to preliminary research conducted using the HSD during commercial wheat harvest, it has been proven that up to 95% of annual ryegrass, wild radish, wild oat, and bromegrass weed seeds can be effectively destroyed (Walsh *et al.*, 2013).

The innovative bale direct system is comprised of a sizeable baler that is directly connected to the combine. This ingenious system expertly constructs bales from the chaff that is discharged from the harvester, effectively capturing the weed seed in the process. As a result, the bales produced are an excellent source of nutrient-rich feed for livestock and can be put to good use (Schwartz *et al.*, 2015).

## Bio Technological Approach

### Herbicide resistance (HR) in crops

Transgenic biotech crops are created by inserting an exogenous herbicide-resistant gene/s from non-plant sources into the desired crop plant. On the other hand, non-transgenic biotech crops are generated for some herbicides by selecting for target mutations in plant populations, or by tissue culture or mutation breeding. As of 2017, approximately 190 million hectares around the world were planted with HR transgenic crops (Rao, 2018).

Transferring an external gene, known as a transgene, is commonly referred to as transgenic engineering or transgenesis. To produce herbicide-resistant crops for select herbicides, plant populations or tissue culture can be screened for target mutations, or mutation breeding can be utilized (Green and Owen, 2011).

The method of utilizing HR crops has been successful in the case of herbicides that target relatively adaptable molecular targets, such as ALS and ACCase inhibitors. These herbicides are susceptible to resistance development, as demonstrated by the evolution of resistance in 160 and 48 species, respectively, solely through target site mutations. (Van Alfen, 2014; Heap, 2018).

### Non-GM herbicide-tolerant rice

The Indian Agricultural Research Institute (IARI) has recently developed two rice varieties that are tolerant to herbicides. These non-GM rice variants, Pusa Basmati 1979 and Pusa Basmati 1985, have a mutated acetolactate synthase (ALS) gene, which allows farmers to use Imazethapyr, a broad-spectrum herbicide, to control weed growth. Dr. Ashok Kumar Singh, the Director of IARI, is credited with developing these rice variants.

### Gene stacking

Crops can be genetically engineered or "stacked" to express multiple traits, making them resistant to multiple herbicides or herbicides and insecticides. This process, known as pyramiding, involves inserting two or more genes with different modes of action into a single plant. An example of a stack is a plant transformed with two or more genes that code for proteins with different modes of action, such as glyphosate resistance and glufosinate resistance or glyphosate resistance and dicamba resistance (Rao, 2018).

### Genome editing

Genome editing tools, particularly CRISPR-Cas9, have revolutionized genome editing technology and are paving the way for sustainable farming in the modern agricultural industry. In this context, we present a chemical method of weed control and approaches for developing herbicide resistance, along with discussing the possible advantages and limitations of using genome editing in herbicide resistance. (Jinek *et al.,* 2012)

**Conclusion**

The study of various scientific fields such as genomics, proteomics, metabolomics, bioinformatics, systems biology, molecular biology, and physiology have immense potential in various areas such as biotechnology, crop improvement, weed management, plant identification tools, molecular assays, and others, which can have a significant impact on weed science and agriculture. Currently, the weed science discipline has reached a critical point. To develop more sustainable integrated weed management and resistance management strategies, it is essential to integrate old and new weed management technologies into more diverse weed management systems based on a better understanding of weed biology and ecology. This approach can be more effective than the present technologies that are failing.

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