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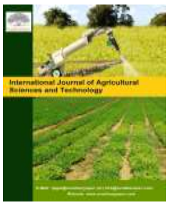

Review Article Open Access

Organic Weed Management in Soybean (*Glycine Max L.*), Recent Trends, Challenges and Future Predictions

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Abstract

Soybean (*Glycine max* L.) is a vital crop with significant contributions to global food security due to its high protein and oil content. However, weed infestation poses a major threat to soybean yield, necessitating effective management strategies. This review explores recent trends, challenges, and future predictions in organic weed management for soybean cultivation. The discussion covers various non-chemical weed control methods, including preventive, cultural, mechanical, thermal, and biological approaches. Preventive measures focus on preventing the introduction and spread of weed species, while cultural practices such as narrow row spacing and high seeding density enhance crop competitiveness. Mechanical and thermal methods provide effective weed control without chemical intervention. Biological control, though less prevalent, offers environmentally friendly alternatives. The review highlights the benefits of weeds in agro-ecosystems, such as reducing soil erosion and enhancing soil structure. It also addresses the challenges of herbicide resistance and the need for integrated weed management (IWM) strategies to reduce herbicide dependency. The future outlook emphasizes the importance of merging conventional and organic weed management practices to achieve sustainable soybean production.

Keywords: *Organic weed management, Soybean, Preventive measures, Cultural practices, Biological control, herbicide resistance, sustainable agriculture*

1. Introduction

Soybean (*Glycine max* L.) is a member of Fabaceae family and rooted from Eastern Asia (China, Korea and Japan) (Degola and Jonkus, 2018). Soybean has the potential to improve soil nutrient availability and agricultural production in the future (Foyer *et al.*, 2019). Soybean holds the crown place and has wide range of uses for human consumption as well as in poultry feed, fish feed, etc. Soybean seed is produced primarily for its edible seed and carry 40% proteins, 20% oil contents and carbohydrates 34% (Munene *et al.*, 2017). Products made from soybeans, including flour, oil, soy milk, soy drinks, snacks, and chunks, have a longer shelf life. Soybean milk is crucial for infants with lactose intolerance (Karuga and Gachanja, 2004). It is a probable answer of global food security insurance. Soybean is distinctive crop and has won many names like 'Golden Bean', 'agriculture Cinderella', 'meat without bone' and 'wonder crop' (Akram and Ahmad, 2019).

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Soybean worldwide production was about 391.17 million metric tons in 2022-23 on a global scale across an area of 122.68 million hectares (ha) according to United States Department of Agriculture (USDA). Brazil with 153, USA with 116.37 Argentina with 45.5 million ton was ranked 1st, 2nd and 3rd, respectively for the worldwide high production of soybean. The total soybean import forecast for the period 2019-2020 is 2.5 million metric tons (USDA, 2022). Weeds are unwanted plants that overtake fields and lowers agricultural production by competing with them for light, water, space and nutrients (Reddy and Reddi, 2011). When a crop is immature and growing, they are very vulnerable to competition from weeds. Yield loss due to weed is depending upon a number of factors, including emergence timing, weed density, species, and variety of crop (Chauhan *et al*. 2020).

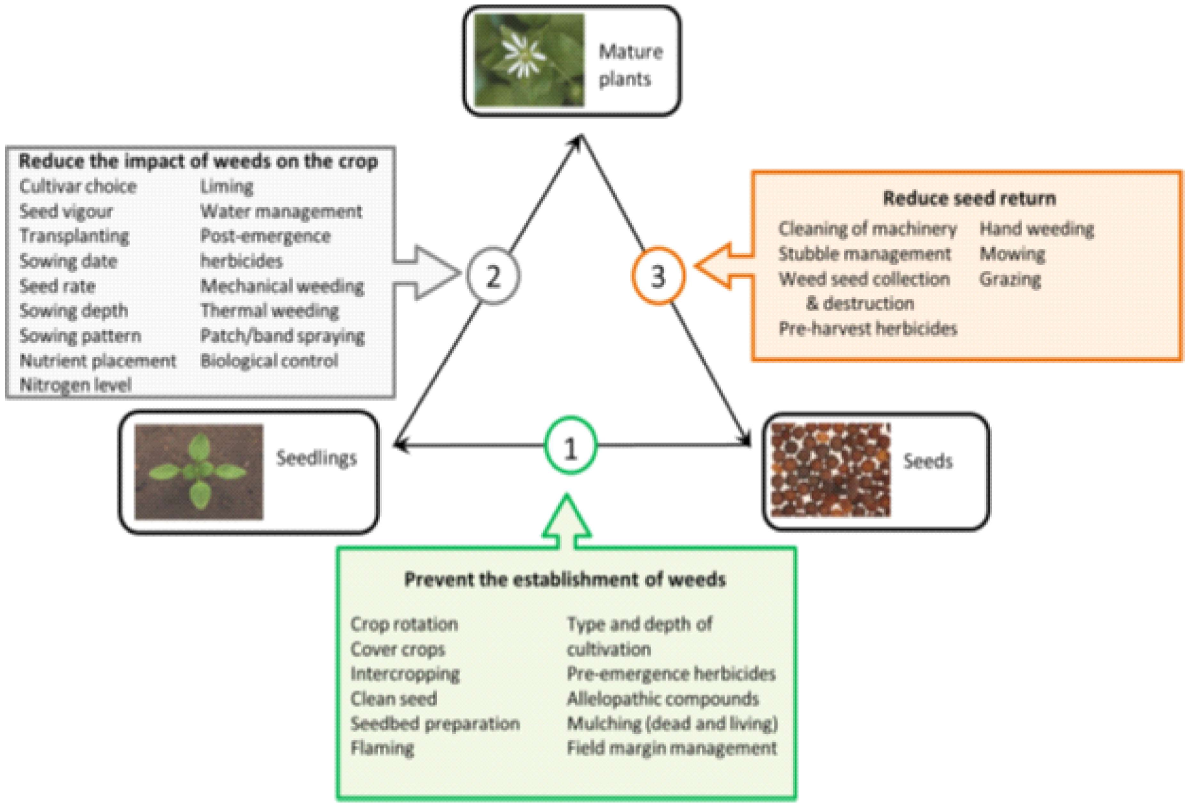

Figure 1: Weed Control Tactics Affecting Weed Survival at Different Stages of Their Life Cycle

Source: Adapted from Kudsk and Mathiassen et al., 2020

Weeds generally cause yield loss because of a variety of species, and the competitiveness of these species can vary greatly (Weaver and Ivany, 1998). Since it is practically impossible to figure out the yield loss caused by a single weed species, the yield loss caused by all the weeds combined is predicted. According to research, weeds have a greater economic impact than fungus, insects, or other pest species (Savary *et al.*, 2000). Weeds accounted for 34% of potential losses worldwide, with animal pests and pathogens having smaller effects (18 and 16%, respectively). According to estimates, weeds reduce agricultural output in most advanced countries by 5% on average, but in less developed countries, the loss is 10%. According to estimates, weeds reduce agricultural productivity by 5% on average in the majority of advanced countries, 10% in developing nations, and 25% in the least developed nations (Oerke, 2006).

Weed infestation is a significant issue in both soybean and other crops due to poor management. If proper weed management is not carried out, a considerable yield loss occurs. In addition to other biotic and abiotic variables, weeds have a detrimental effect on the typical crop yield. According to reports, weed infestation gone unchecked resulted in up to a 43% decrease in crop productivity globally (Oerke, 2006). Average production losses caused by weeds in several crops are substantially higher in Pakistan (11.5%) than that of globally (9.5%). Therefore, weed control is crucial for enhancing crop productivity (Marwat *et al.*, 2008).

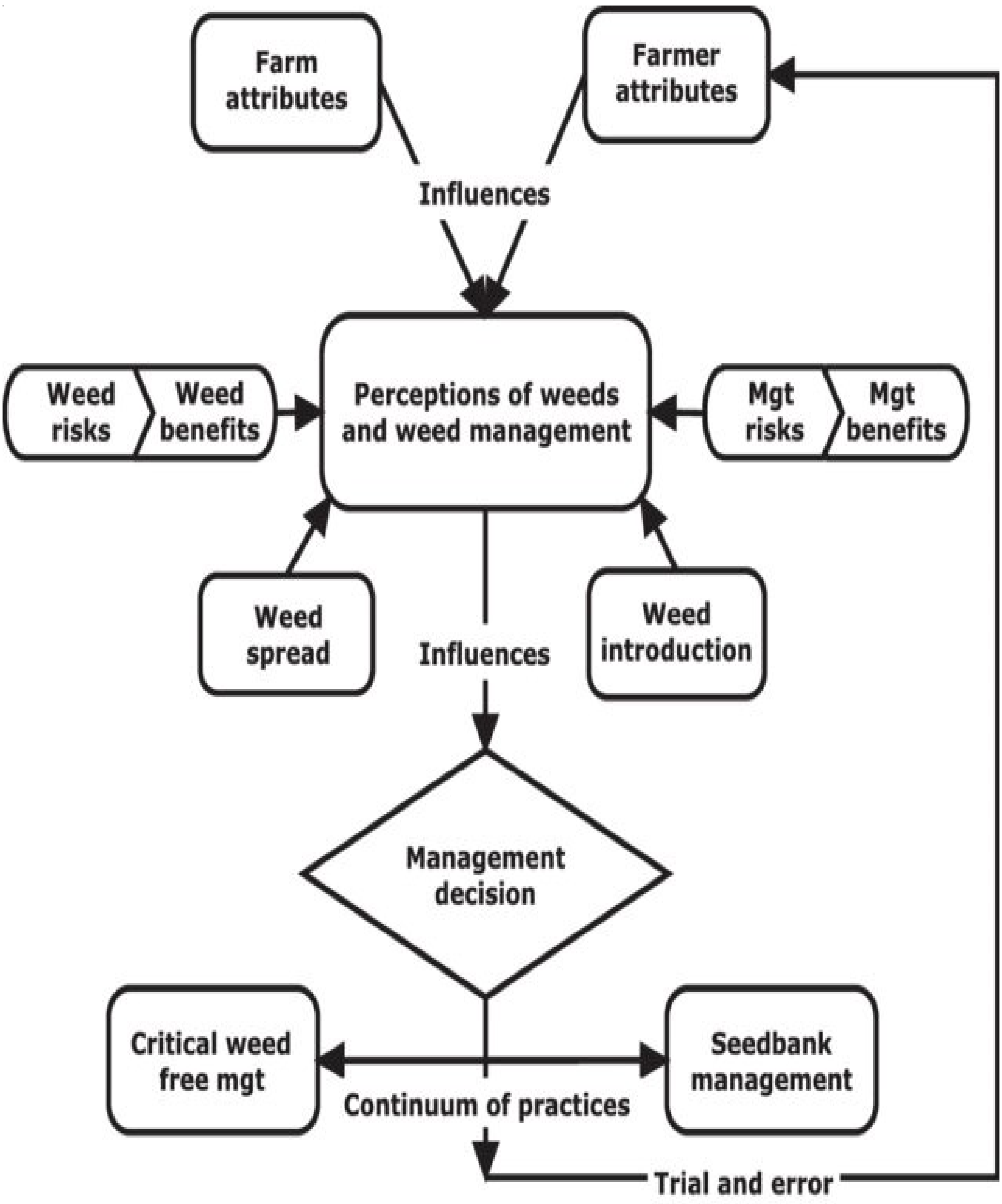

Figure 2: Conceptual Model Representing the Expert View of the Organic Weed Management Decision-making Process

Source: Jabbour et al., 2014

2. Impact of Weed Infestation on Soybean Yield and Quality

In both agro- and eco-systems, the existence of weeds is frequently linked to a number of negative impacts, the most significant and extensive of which is the decrease in crop output. In 2018, Zimdahl offered a comprehensive list of losses in yield along with their corresponding costs. Allelopathy, parasitism, and weed competition are factors that reduce crop output. Due to the high synergism between allelopathy and competition in nature, it should be noted that allelopathy refers to the release of chemicals into the environment that have either positive or negative effects, while competition refers to the reduction or removal of an important resource for life (such as light, water, nutrients, space, etc.) by another plant sharing a similar habitat (Scavo *et al.*, 2018).

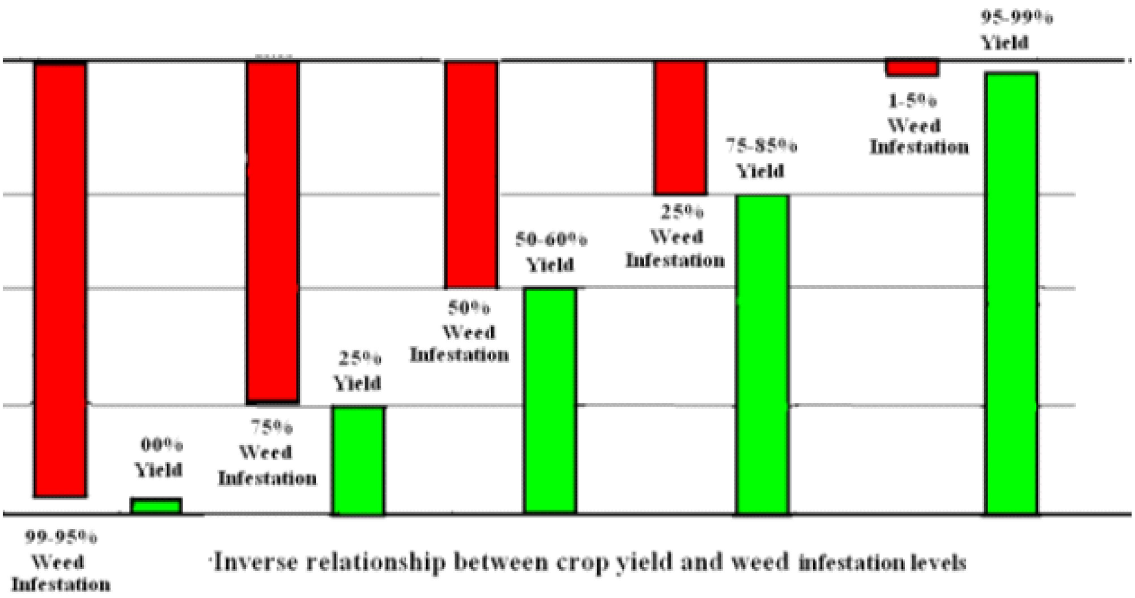

Figure 3: Inverse Relationship Between Crop Yield and Weed Infestation Levels

Source: Leghari et al., 2015

Over 240 weeds that are allelopathic to crops have been found and reported by Qasem and Foy (2001). Muller (1969) introduced the word "interference" to refer to the combined negative effects of allelopathy and competition on a plant, given the challenge of distinguishing and characterising allelopathic effects from those caused by competition (Zimdahl, 2018). The amount of crop–weed interference is influenced by a variety of factors that can act antagonistically, additively, or synergistically. These factors include the genotypes of the crop and the weed, as well as agronomic and environmental factors. Examples of these factors include relative growth rates, root system development, emergence time, seed size, and seedling vigour. When weeds are not controlled in agricultural farming systems, there is a total crop failure (100% yield loss). Crop output eventually drops under a reductive strategy as plant density rises. The goal of creating

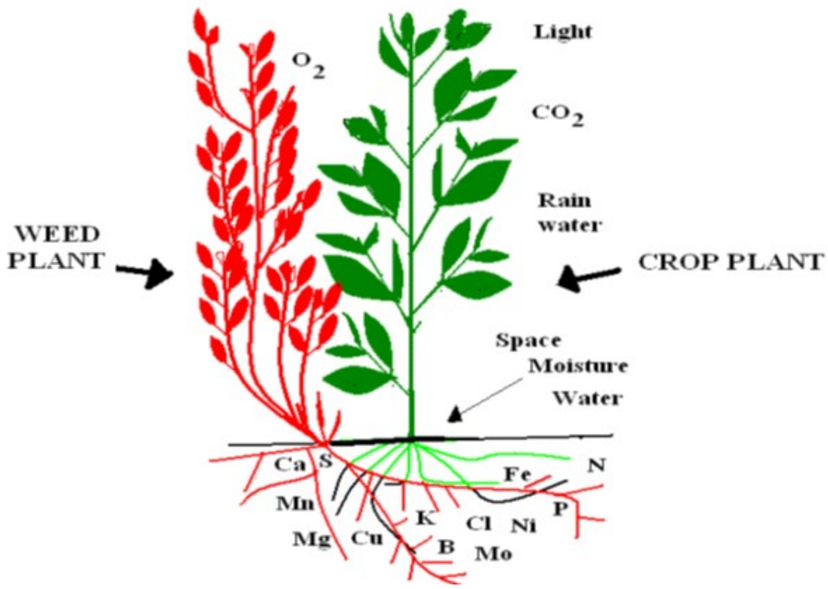

Figure 4: Weed Plant Giving Tough Time to the Main Crop Plant for Growth in Different Ways for Different Resources

Source: Leghari et al., 2015

economic weed thresholds as a foundation for weed management decisions has led to the development of a number of bio-economic and predictive yield models since the 1980s in an effort to understand the impacts of weed existence on crop productivity in a better way.

Weeds can also directly affect the dietary quality of agricultural products, causing qualitative degradation through food contamination or other means. Additionally, according to Qasem and Foy (2021), weeds can host pest insects and other crop diseases, increase the cost of production and processing (e.g., by interfering with agricultural operations like mechanical tillage), lowers the value of land (especially when it comes to parasitic and perennial weeds), restrict crop's selection, interference in the water management (e.g., by increasing evapo-transpirative water losses, decreasing water flow in irrigation drains, etc.), and harm humans in recreational areas. Additionally, weeds can induce a variety of allergic reactions in humans (Zimdahl, 2018).

2.1. Ecological and Agronomic Benefits of Low-Density Weeds in Soybean Cropping Systems

The occurrence of weeds also has a number of economic and ecological (i.e., enhancing biodiversity) benefits, especially when they are present at low concentrations. Deep and wide-ranging root systems in weeds help retain soil moisture, minimize soil erosion and minerals nutrient loss, and enhance the structure of soil. The decline in precipitation action and the branched and fibrous root systems of mono-cotyledonous weeds like Cynodon spp., Digitaria spp., Echinochloa crus-galli (L.) P. Beauv., Agropyron spp., etc. are the two main causes of the reduction in soil erosion. These weeds have the potential to enhance soil structure and water retention capacity by increasing water infiltration through root branching and depth. The latter phenomenon can be explained both physically and by the root exudation mechanism, which encourages the development of aggregates by stimulating microorganisms and the adsorption of rhizodeposits (e.g., ions like Fe2+, Al3+, Ca2+, K+, mucillages, and numerous organic acids) with colloids (Scavo *et al.*, 2019). Furthermore, the combination of exudates from roots and mulch made of both living and dead weeds helps to increase the amount of organic matter in the soil. However, it has been observed that in certain circumstances, a moderate amount of weeds can raise the nitrogen content of the soil by lowering nitrate losses through leaching and by allowing Fabaceae species to fix nitrogen dioxide with rhizosphere bacteria. For instance, Kapoor and Ramakrishnan (1975) discovered that growing wheat in conjunction with Medicago polyceratia (L.) Trautv significantly increased the dry weight yield of the crop. Due to these factors, weeds are viewed as essential components of the agroecosystem in modern cropping systems and should not be thought of as objects to be eradicated but rather as organisms that play a variety of agro-ecological roles and need to be controlled. According to Jordan and Vatovec's (1975) "ecological restoration" theory of weed management, weeds should be acknowledged as a normal and controllable component of the agro-ecosystem, and the goal of weed management should be to lessen negative consequences and promote positive effects brought about by this flora.

2.2. Embracing Organic Farming: Non-Chemical Weed Management for Sustainable Soybean Production

In today's agriculture, where resources are limited and the need for food grains is rising daily, one of the main issues is sustainable crop production. Abiotic and biotic stressors are the causes of agricultural productivity losses. Similar to abiotic factors, which include excessive or insufficient water throughout the growth season, high or low temperatures, irradiance, and nutrient availability, biotic stressors can likewise significantly lower yields (Oerke, 2006). The primary biotic restrictions to agricultural productivity are considered to be weeds. The main agricultural pest that can ruin a crop if improperly controlled is weeds.

Since the extensive utilisation of agrochemicals has led to problems regarding environmental health and the establishment of herbicide resistance in weeds, some farmers are showing a revival of interest in organic techniques for managing weeds. The biggest issue affecting organic farmers' productivity is weeds. It is critical to know that a farmer who practices organics is dependent on non-chemical weed control. Sustainable agricultural production requires non-chemical weed control (Kavita and Bhupendra, 2022).

Herbicide use has been on higher levels in less developed nations during the past few decades (Moody, 1990). The most widely used broad-spectrum herbicide worldwide is glyphosate-based. Glyphosate is widely present in aquatic as well as terrestrial environments as a result of its over-application activities (Hanke *et al.*, 2010). It has been discovered that glyphosate spray drift causes damaged fruit at sublethal levels of exposure (Laitinen *et al.*, 2007). Furthermore, specialists from the International Agency for Cancer Research of the World Health Organization have determined that glyphosate causes cancer among humans (Myers *et al.*, 2016). This highlights the harmful effects of the herbicides on the economy, ecology, and public health. This pushes us to switch to organic farming methods in future. Considering this, I made an effort to compile a few organic or non-chemical weed-control techniques for this article.

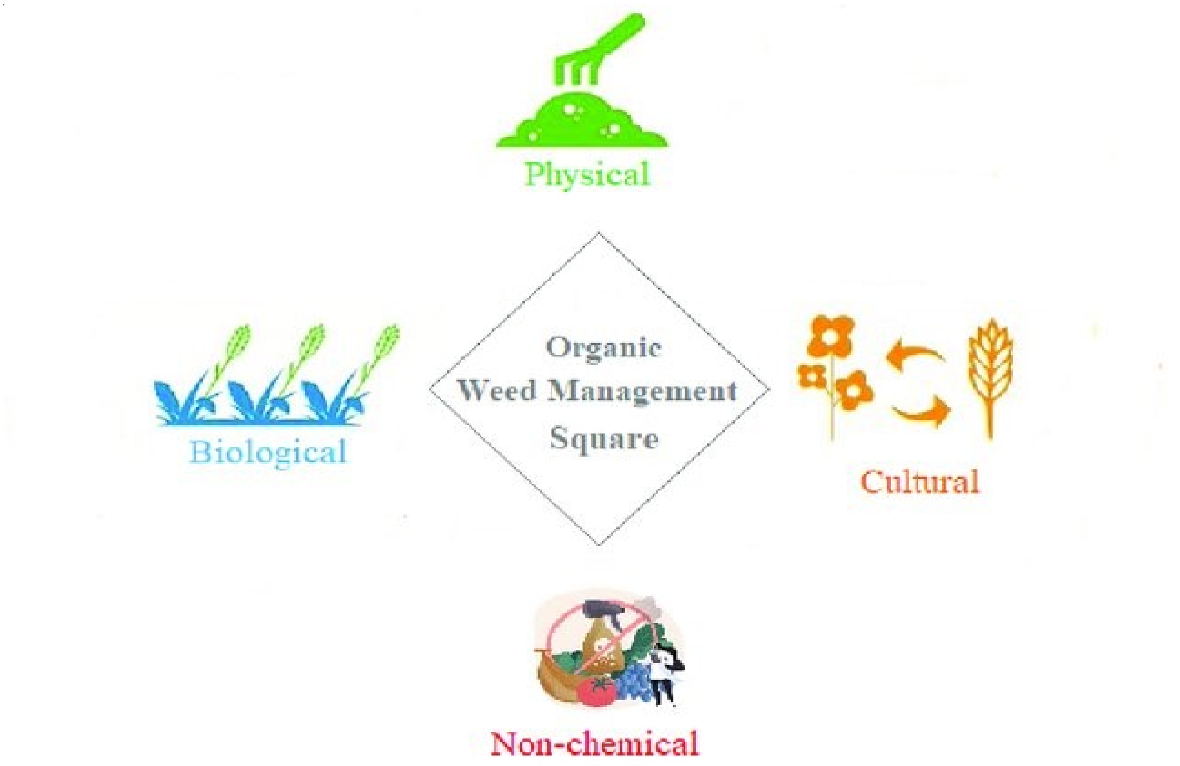

Figure 5: Organic Weed Management Square

Source: Özyazici, 2021

Chemical treatment is prohibited in organic farming systems for the purpose of weed control, as per the United Kingdom Register of Organic Food Standards (UKROFS, 1999) and similar national guidelines across Europe, which are based on regulation no. 2092/91 of the European Community. According to a recent poll, organic growers in the UK

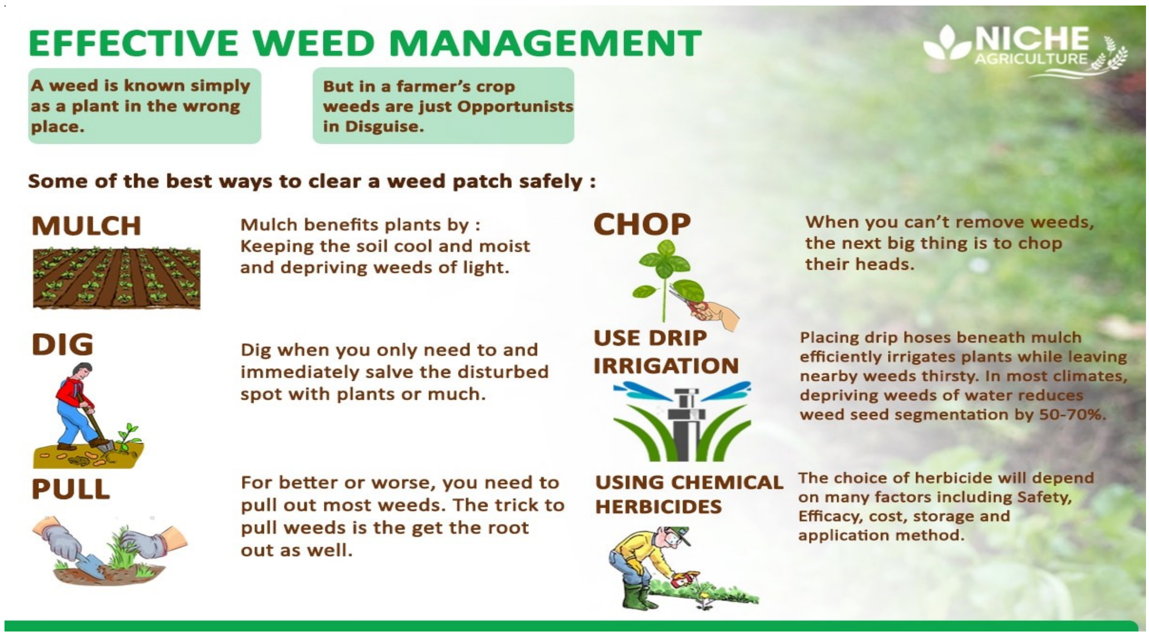

Figure 6: Effective Weed Management

Source: Niche Agriculture, 2024

thought their present weed management was sufficient, but few thought the direct weed control techniques were particularly effective (Beveridge and Naylor, 1999). Three years after switching to organic farming, an analysis of the relative frequency of weeds revealed that the total quantity of seeds in the soil raised by 4050 m^2 to 17320 m^2 (Albrecht and Sommer, 1998). One of the main things keeping conventional growers from adopting organic farming is their fear of the negative effects of controlling weeds without using pesticides (Bond and Grundy, 1998).

3. Weed Control Methods in Soybean

3.1. Proactive Strategies: Preventive Weed Control Methods for Sustainable Soybean Cultivation

When weeds established, they are usually more difficult to eradicate, thus it is usually less expensive and easier to stop them from invading a new region. The application of techniques designed to stop the invasion, establishment, or growth of specific problematical species in regions that are not yet afflicted with them is known as preventative control of weeds (Silva *et al.,* 2007). These regions might be a nation, a state, a town, or a section of the farm. There are rules governing the domestic commercialization of seeds and their introduction into the nation or state at both the federal and state levels. These laws specify the maximum amount of seeds allowed for each type of weed as well as the list of seeds that are not allowed for any certain crop or crop's category. Locally, it is the duty of each farmer or agricultural cooperatives to stop the introduction and spread of any weed species that could pose a major threat to the area. In conclusion, preventive control relies heavily on the human factor.

A good crop can be thought of as integrating cultural and preventive methods when it effectively occupies the space in the agro-ecosystem, hence reducing the availability of favourable conditions for weed growth and development. Actually, the first stage of effectively establishing a crop is selecting the appropriate genotypes. When it comes to soybeans, there are numerous varieties that are suited to various regions around the world. Use of high-purity seeds, cautious cleaning of harrows, harvesters, and other machinery, careful inspection of seedlings come by soil and all organic matter (manure or compost) from other sites, clean channels for irrigation, isolation of introduced animals, etc. are some of the steps that can stop the introduction of the species (Radosevich *et al.*, 2007) and (Chauhan *et al*. 2012).

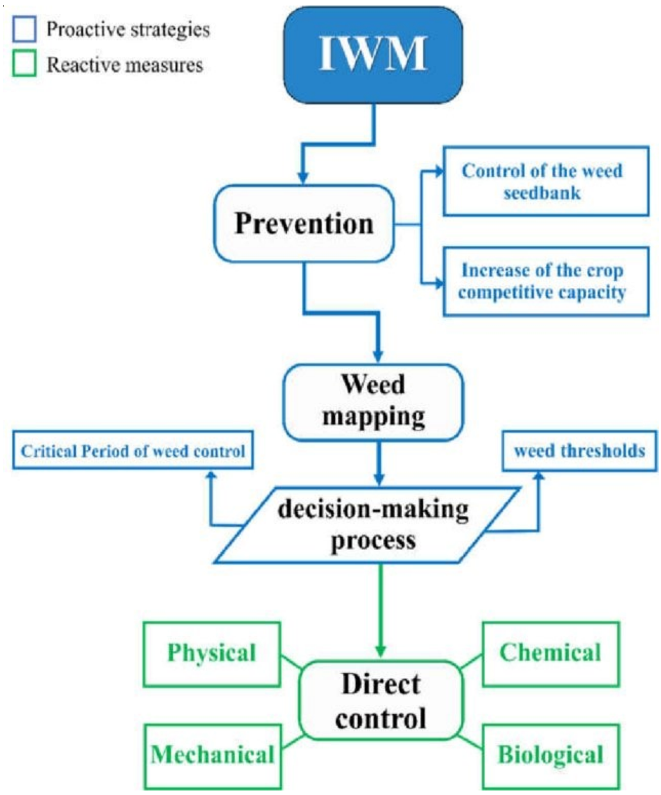

Figure 7: Proactive and Reactive Tactics of an Integrated Weed Management (IWM) Strategy

Source: Scavo and Mauromicale, 2020

Accept that weeds contaminate the seeds of most crops, particularly when the weed seeds mimic the size and appearance of crop seeds. When weeds with life cycles comparable to crop cycles set seeds, contamination typically occurs while crop harvesting. A little quantity of weed seeds could be sufficient for a significant infestation for the following year. Reducing the area where weeds are infested and the amount of weed seeds that spread from a particular crop to another should be the goals. Plants and propagules are reduced to the extent that they no longer significantly hinder an area used for commercial purposes in order to control weed species. Strategies for controlling post-infestation weeds should be planned so that the accumulation of seeds from weeds is significantly decreased in a short span of time. Integrated weed management strategies should be used with caution to limit the amount of the weed seed bank in the region. Weed and volunteer crop seeds are deposited in the topsoil of systems that are not disturbed or unhealthy. In order to avoid excessive weed infestations and unfavourable competition with the growing crop, a suitable strategy is therefore required (Locke *et al.*, 2002).

3.2. Effective Cultural Strategies for Weed Management in Soybean Cultivation

Weed dynamics are impacted by cultural techniques such close row spacing, dense seeding, cover crops, and choosing cultivars that can quickly close their canopy (Grichar *et al*., 2004).

Row Spacing: Row spacing and time of emergence have been found to have a major impact on weed's competitive index (CI) values. For example, Hock *et al.* (2006) found that for three common soybean weeds i.e. Halianthus annuus, Xanthium strumarium, and Abutilon theophrasti, the competitive index values for total dry matter in 76 cm of rows spacing were 10, 4.53, and 2.08, respectively; for 19 cm of rows spacing, these figures were 7.33, 2.99, and 1.27, respectively. In the same way, emergence time has a big impact on CI values. When the same weed species arose in 76-centimeter rows at the VE (emergence) stage, the CI values were 10, 3.59, and 0.54, while the values were 3.74, 1.17, and 0.34, respectively.

In addition to giving plants the best conditions for increased development and productivity, the right row width promotes effective weed management. In soybeans, extensive research has shown that narrower rows produce better yields and are better at controlling weeds than broader ones (Bradley, 2006). Less than 76 centimeters between rows was determined to be preferable to larger row spacing. Reducing row spacing and managing early-emerging weeds could be successful weed management tactics for soybeans (Hock *et al*., 2009). By preventing light from penetrating the soil's surface and shortening the time it takes for soybeans to reach full closure of canopy, narrow spacing improves weed control (Bradley, 2006). When soybeans were grown in narrow rows for a large portion of the growing season, Puricelli *et al.* (2003) found that there was a considerable decrease in light penetration to the soil surface as opposed to broader rows. Dalley *et al.* (2004) similarly reported similar results. Compared to wider rows, narrower soybean plantings increased early season resistance to weeds and postponed the critical time for weed removal (CTWR). According to Knezevic *et al*. (2003), a wider row spacing of 76 cm required earlier weed treatment than a closer row spacing, which decreased the early-season resistance of soybean to weeds.

Seed Density: Large seeding rates and narrow row spacing enable the crop combat with weeds for vital resources (Grichar *et al.*, 2004). Complete weed suppression is achieved by higher plant population because of higher levels in plant biomass (Weiner *et al.,* 2001). Increased seeding density/plant's population is one of the greatest strategies for managing weeds in soybeans, according to numerous researches. According to Norsworthy and Oliver (2002), a 729,000 plant ha-1 increase in the number of soybeans enhanced the efficiency of weed control from 60% to 91%.

Crop competitiveness based on seeding density is equally significant for conventional and organic soybean cultivation. According to Dimitrie and Greene (2002), there is a rapidly growing global demand for food items and even feed that is produced organically. The major uses of organic soybean are in the production of numerous organic food items and feed diets. Increased planting density in organic soybean can help achieve desired weed control (Place *et al.,* 2009). Place *et al.* (2009) conducted a study in the USA comparing four different seed rates (185,000, 309,000, 432,000, and 556,000 viable seeds ha^{-1}). The results indicated that the rate of 556,000 viable seeds ha-1 offered superior weed control in addition to improved yield and enhanced profits. According to Coulter *et al.* (2011), seeding rate was not as important as early planting for yield and weed control in organic soybean. They found that planting soybeans in mid to late May rather than in mid of June improved both weeds control and yield for the majority of the soybean genotypes that are produced organically, although increasing the planting rates from 395,400 to 543,600 plants ha^{-1} did not increase either.

Crop competitiveness against weeds may also be influenced by the size of its seeds. According to Place *et al*. (2011), planting larger seeds increased plant height and petiole length, which increased soybean competitiveness and improved control of weeds in organic soybean production. According to Arce *et al*. (2009), the Glyphosate-Tolerance soybean plant population had a negative influence on weed biomass during the soybean harvest phase, but had a small impact on the population of weeds during the growing period.

Cultivars: Any species that can dominate its neighbour for resources including light, water, space, and nutrients is considered competitive. According to some research, the best yielding cultivars under weeds-free condition will also generate the highest output and be the best competitor against weeds if different species of weed or weed's pressure has no effect on the competitive rate of soybean cultivars (Grime, 2001).

The competitiveness of different soybean cultivars against various weeds varies (Zimdahl, 2004). There have been reports of variations in biomass of weed upto 45% as a result of growing different soybean varieties (Rose *et al.*, 1984). Rezvani *et al*. (2013) recorded total relative biomass, competitive balance index, and respective crowding coefficient to assess six soybean varieties for weed suppression performance and competitive index. All of the soybean varieties had a decrease in height, yield, and yield components due to weeds; however, differences in competing across the tested varieties were shown by the values of the weed suppressive ability and competitive index. According to Rose *et al.* (1984), the following variables affect a soybean cultivar's ability to compete: (i) rate of emergence relative to competing weeds; (ii) seedling vigour; (iii) canopy closure rate; and (iv) allelopathic characteristics. According to Norsworthy and Shipe (2006), competition may be associated with a number of complex or at least challenging to quantify qualities, or combinations of attributes. To improve weed management in soybean, which requires genetic variety in the weed-soybean interactions, breeding cultivars with enhanced weed suppression potential would be more effective strategy (Vollmann *et al.*, 2010).

While suppression of weed and tolerance of crop to weeds are related to leaf area index and interception differences of light in maize (*Zea mays* L.), weed suppression in rice (*Oryza sativa* L.) during the initial phases of crop growth is related to leaf area (Gibson *et al.,* 2003; Lindquist and Mortensen, 1998). Such comparable traits can also be used to choose competitive cultivars of soybeans. Measurements such as height of plant, width of plant, canopy volume, early season growth rate, and visual estimate of ground cover may be helpful in choosing competitive cultivars of soybeans (Rose *et al.*, 1984; Norsworthy and Shipe, 2006). According to Norsworthy and Shipe (2006), field cover of soybean is especially crucial to competition because it reduces weed emergence as the rate of canopy formation rises with reducing width of rows and rising population.

The majority of studies assessing soybeans' capacity for competition have screened cultivars against a small number of weed types or several types at a single proportion of competition. Information regarding the competitive interactions between various weeds species and the impact of weed pressure on the ability of various soybean cultivars to compete has been limited. A producer can make effective decisions when there is only one type of weed species present in the field. However, when multiple weed species are common, such decisions become extremely challenging because of different densities, emergence times, and environmental conditions distinctive to each site (Knezevic *et al.*, 2002; Evans *et al.*, 2003; Rasheed, 2024).

Cover Crops: Herbicide use must be decreased through the employment of alternative weed-control techniques. Using cover crop interseeding is one of these solutions. According to Uchino *et al*. (2009), inter-seeding is the practice of sowing major crops into established vegetation. Since the 1950s, weed control in soybean has been achieved through the use of companion crops, such as rye (*Secale cereale* L.), and narrowing row spacing (Robinson and Dunham, 1954). The impact of interseeding cover crops inside primary crops has been assessed in numerous researches. When planted three weeks after the actual crop in an organic farming system, winter rye, a cover crop, greatly reduced weeds without reducing crop output (Uchino *et al*., 2009). Liebl *et al*. (1992) found that using S. cereale as mulch on soybeans produced good weed control, with the exception of C. album. The best cover crops for suppressing weeds were determined to be hairy vetch (Vicia villosa Roth.) and winter S. cereale (Uchino *et al.*, 2005; Aleem, 2024).

Particularly in organic agricultural systems, cover crops are an excellent substitute for pesticides for weed suppression. The cover crop decreased the density of weeds in maize by 29% and soybeans by 59%. To produce more efficient cover crop weed suppression, it is necessary to have knowledge about the growth patterns of the actual crop, the types of cover crops, and weeds, in addition to environmental and field factors (Uchino *et al.*, 2009; Pervaiz *et al*., 2024). Understanding the geographical dispersion of weed is also crucial for effective weed control.

However, the cover crops may also put the primary crop in competition. The date of the cover crop's sowing is crucial. When rye was planted as a cover crop prior to or simultaneously with soybeans, the main crop's biomass was drastically reduced. Even though the cover crop was much smaller in height than the actual crop, planting it earlier had a negative impact on the main crop's chlorophyll concentration as well. The main crop's biomass and chlorophyll content were barely affected by the cover crop sown later than the primary crop (Uchino *et al*., 2009).

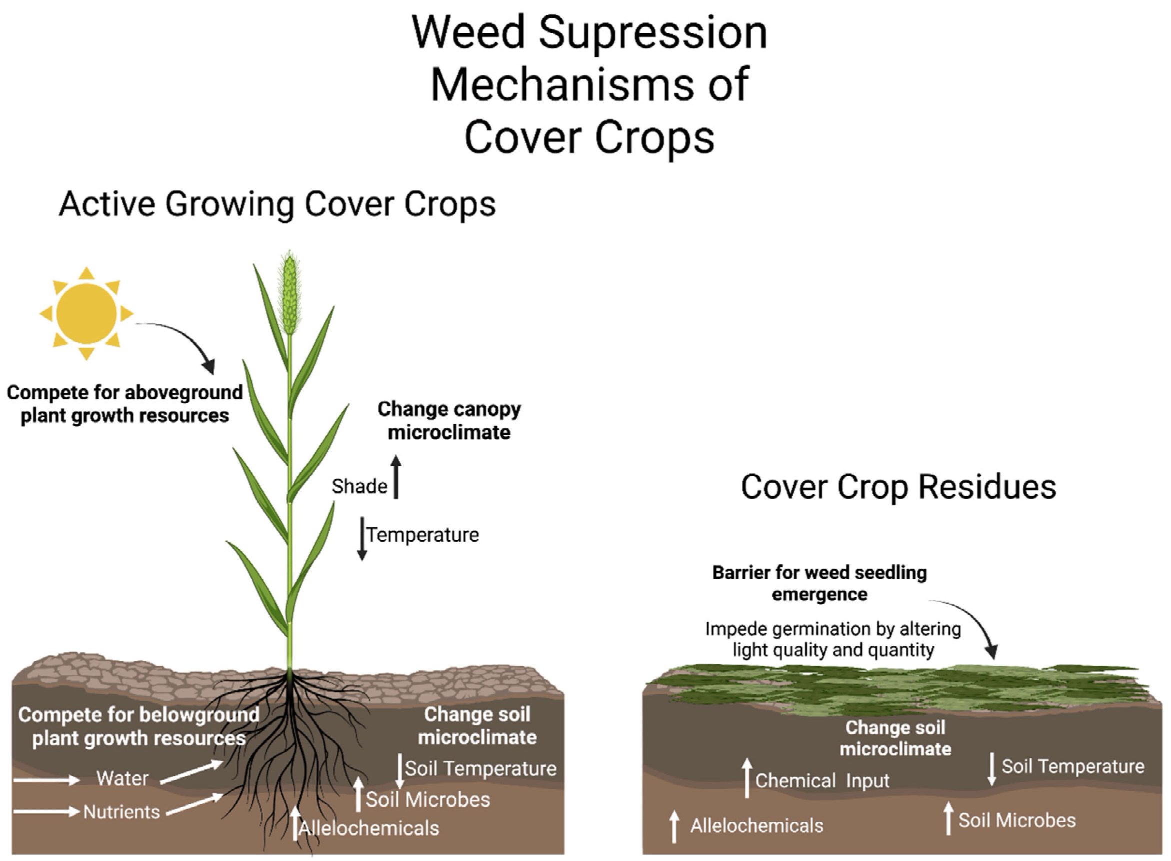

Figure 8: Conceptual Diagram of a summary of possible interactions during the actively growing phase of the cover crop (left) and after the cover crop is terminated and left as a surface residue on the soil (right)

Source: Fernando and Anil, 2023

3.3. Physical Control Techniques for Effective Weed Management in Soybean Cultivation

Physical weeds management includes pulling weeds with hand, using tools and machinery, or using heating techniques (Stockdale *et al.*, 2001).

4. Mechanical Methods

Tillage: Tillage is the main method of weed control in conservative, low-input, and organic agricultural systems (Dogan *et al.*, 2014; Arshad *et al.*, 2024c). Mechanical weed management is typically applied in post-emergence between or within rows. Tillage's primary objectives when used in pre-emergence are to manage the weed seed-bank in soil and improve the ability of crop to combat with weeds in the beginning phases. Tillage's herbicidal effect is achieved by altering the vertical dispersal of the seed-bank: variations in microclimatic conditions (temperature, aeration, and light) considerably lessen the germination of weed seeds buried in soil, while on the other hand, weed seeds and growing propagules on the surface of soil are more susceptible to attack and physiological death (Gallandt, 2006; Eslami, 2014; Akhter *et al.*, 2017).

The eradication of established weeds, particularly perennial weeds that grows from vegetative portions like stored roots, rhizome or other underground structures, sometimes requires tillage. Tillage includes weeds being pulled up and chopped. In addition, depending on the tool(s) employed, it may involve burying weeds and their seeds, or association of all of these methods. Since most tillage techniques are effective at getting rid of existing weeds, their impact on seeds—both in the soil and on the plant, can range from a complete elimination to significant increase in the emergence of following seeds. Different weed species react differently to mechanical control because of differences in their life cycles Therefore, when choosing the time and instruments for primary or secondary tillage, the weeds that are present must be taken into account (Schonbeck, 2019; Rafeeq *et al.*, 2020).

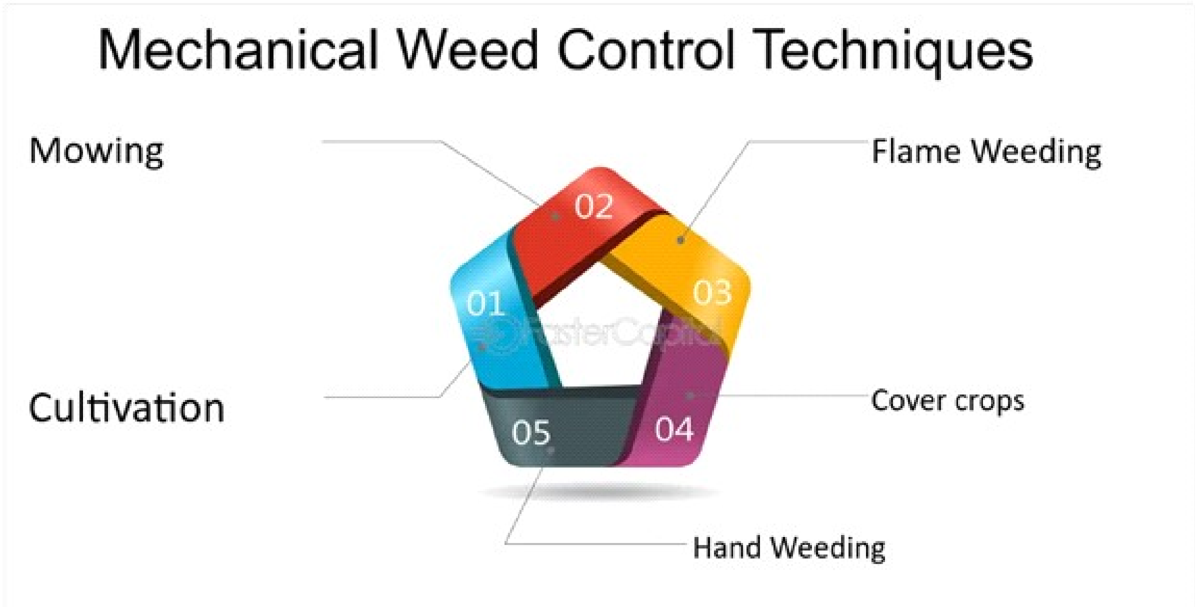

Figure 9: Mechanical Weed Control Techniques

Figure 10: Tillage Weed Management in Soybean

Source: Einböck. 2024

It is crucial to point out that meteorological conditions have a significant impact on how well tillage controls weeds. The easiest way to control weeds is to do tillage on a hot, bright day so that noxious weeds with extensive underground rhizomes are carried out and allowed to shrink. Tilling moist soil causes it to contract and loses its texture, which encourages weed species that like hard soils and hinders the growth of crops in the future. Weeds have the ability to re-grow if rainy weather follows tillage. Weed seed germination can be prevented and the impact of a stale seedbed can be diminished if initial ploughing is followed by cold, wet weather (Howell and Martens, 2022).

Blind Cultivation: The basic and most efficient mechanical weed management technique is blind cultivation since the crop & the weed are not the same height. This technique involves cultivating fields without considering where the field rows should be placed. The aim of blind cultivation is to uproot weeds with shallow roots in the 2 to 5 cm of topsoil, resulting in a significant number of little weed seeds (which are still germination-processing) drying up and wilting. Large crop seeds are not harmed by blind culture since they sprout below the sowing depth. Crop seedlings can develop when a soil crust is broken by blind cultivation. Regardless of where the rows are located, executes for accurate weed suppressing and control can be brought across the field at comparatively higher rates (5 to 10 km/h) (Howell and Martens, 2022).

Figure 11: Blind Cultivation Weed Management for Organic Soybean

Thermal weeding method: There are two types of thermal weeding techniques: high-temperature and low-temperature techniques. Liquid nitrogen is used in low-temperature weeding techniques, whereas steam or hot water (HW), infrared

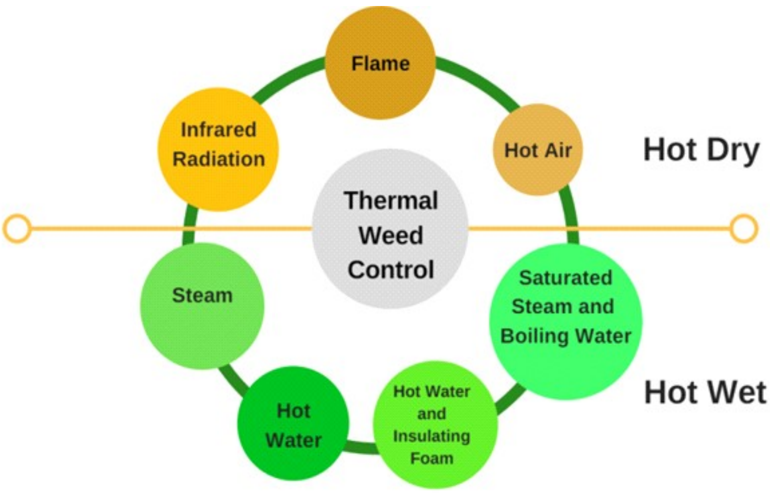

Figure 12: Thermal Weeding Method

radiations (IR), open flames (OF), and microwave radiations are used in high-temperature weeding techniques. Crops cultivation, glass houses, public parks, and the playground have all made use of HW, IR, and OF. Since there is no flame, there is no danger of fire risk when HW is applied straight to the weeds. Without worrying about soil drifting, runoff from the surface, or efficacy loss, HW can be sprayed in a variety of weather circumstances, including windy and wet ones (Stockdale et al., 2001; Abbas *et al.*, 2021a).

When cultivating vegetables, many farmer's employs propane flame burners, either back-pack or tractor-mounted, to eradicate small weeds right before planting. With this equipment, the entire field is aflame. In order to preserve their crops, growers who utilize propane's flame weeding between the rows construct unique heat proof barriers. Burning an old seedbed is a common method used by organic farmers to get rid of immature weeds without affecting the soil. It is carried out right before or right after planting crop. These equipments use less energy because they include flame covers or protections that direct the heat towards the desired weeds (Schonbeck, 2019; Arshad *et al.*, 2021). Diver (2002) stated that burning works best and uses the least amount of energy on weeds that are no more than 5 cm tall. According to Lague *et al*. (2001), if the OF method is applied to leaf area of plant with flames for atleast 0.1 second at temperatures as high as 1000°C, the inner water in the cell boils and the cell membrane collapse, causing dehydration and death.

Figure 13: Thermal Weed Control Using Hot Water Treatment

Source: Nisa et al., 2020

4.1. Innovative Biological Control Strategies for Sustainable Weed Management

The (EWRS) European Weed Research Society stated that "Biological management of weed is the intentional utilization of native or invasive organisms (primarily phyto-phagous, plant pathogens nematodes and arthropods) for controlling of target weed population". The biological control of weeds is defined by the Weed Science Society of America as "the utilization of an agent, an intricate combination of agents, or biological mechanisms to achieve weed control," with the clarification that all microbial and macrobial organisms are included in this definition. Bio-control agents were classified by Cordeau *et al*. (2016) into four categories: natural chemicals (derived from plants or animals), chemical mediators (like pheromones), microorganisms (including bacteria, fungi, and viruses), and macro-organisms (such predators, parasitoid insects, and nematodes). Since the 1980s, researchers, organisations, and stakeholders have paid particular attention to biological control on a global scale. This increase is being attributed to organic farming and sustainable agriculture. Schwarzländer *et al*. (2018) used data from the fifth edition of "Biological control of weeds: a world categorize of agents and their target weeds" to state that: (i) the five nations most involved in bio-control research and releases are, in decreasing order, Australia, North America, South Africa, Hawaii, and New Zealand; (ii) three insect orders—Lepidoptera, Diptera and Coleoptera—accounted for approximately 80% of all bio-control agent species released; and (iii) 66% of the weeds targeted for biological control saw some degree of control.

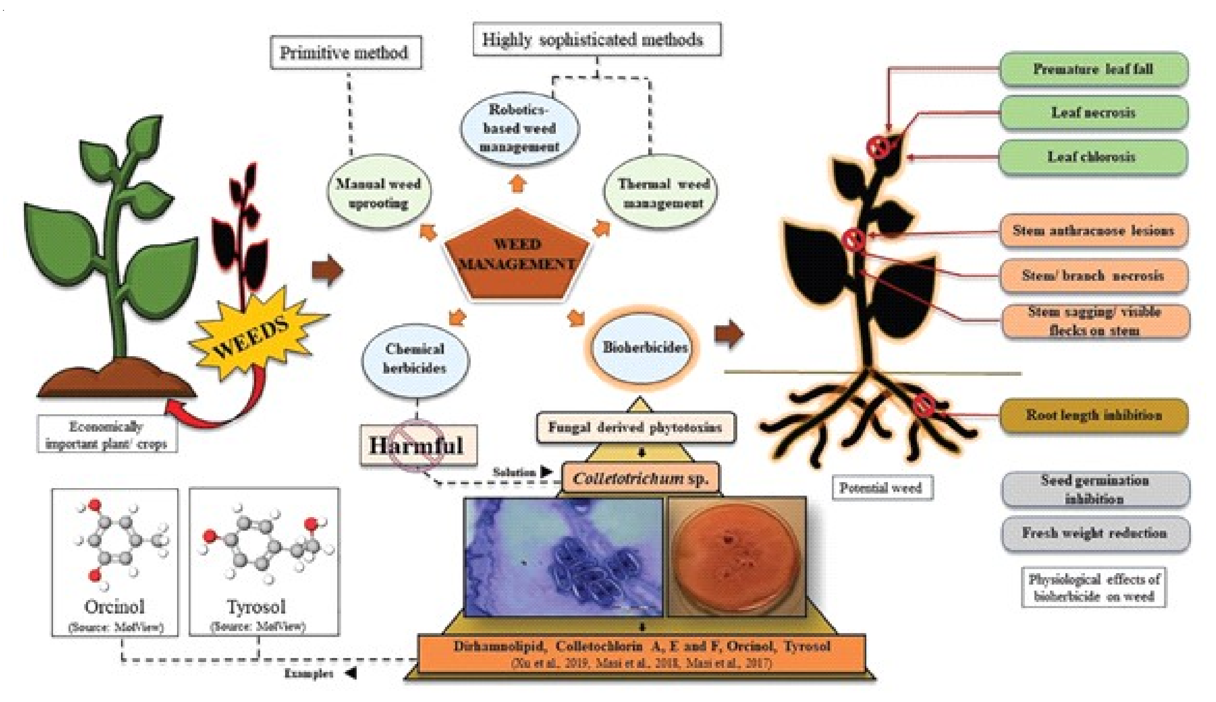

Figure 14: Graphical Representation of Weed Management Strategies Using Bio Herbicides

Source: Masi et al., 2017; Masi et al., 2018; Xu et al., 2019

Sheppard *et al*. (2006), Müller-Schärer and Collins (2012), and Charudattan (2001) have all presented comprehensive evaluations and lists of real-world applications. The market share of bio-herbicides, or products of natural source for weed control, is less than 10% of all bio-pesticides, which include bio-fungicides, bio-bactericides, bio-insecticides, and bio-nematicides, despite the growing interest in biological control tools (Charudattan, 2001). Myco-herbicides, including DeVine®, Collego®, Smoulder®, Chontrol®, and others, represent the majority of bio-herbicides that are actually sold in commercial formulations. Compared to synthetic herbicides, bio-herbicides have new mode of action and molecular target site in addition to being accepted by the public and acting in an environmentally beneficial manner (Duke *et al.*, 2000). However, their shorter half-life and lower field efficiency dependability than chemicals, along with the requirement to be developed with coformulants and encapsulated—procedures that demand a great deal of time, money, and collaboration between public and private groups—all contribute to the low number of commercial formulates (Dayan *et al*., 2012; Mejias *et al.*, 2019; Abbas *et al.*, 2021). According to Charudattan (2001), out of all ongoing bio-herbicide projects, only 8% were successful and 91.5% were not relevant.

4.2. Future Prospects in Weed Management: Integrating Sustainable Practices and Reducing Herbicide Dependence

It is evident from the global history of herbicide resistance (HR) weed control that growers address the issue after it arises rather than before (Beckie, 2006). Moreover, the volume (dispersal and abundance) and intricacy (multiple and cross resistance trends) of their herbicides resistance weed population in their fields determine how much their farming system will alter. Growing numbers of growers now have to consider crop rotations or crop switching in order to control HR weeds with the herbicides that are still working. For instance, from 2000 to 2016, the proportion of UK farms using spring cropping to control HR grassy weeds, like black grass, risen from 32 to 81% (Moss, 2019). Because of their poor weed competitiveness, lack of registered herbicides, or reliance on small number of herbicide sites of action, such as Aceto-Lactate Synthase inhibitors, annual legumes crops are typically the weak link in the rotation. The highest risk of falling planting area and productivity is associated with these crop varieties. Effective pre herbicides in conjunction with agronomic techniques to enhance crop’s competition and reduce weeds seed establishment or seed-bank restoration have been shown in Australia over the past ten years to typically produce beneficial grain crop production and persistently low levels of problematic weed seed banks.

Reduced reliance on herbicides, particularly glyphosate, should be at the forefront of the global HR weed management strategy going forward. Rather than being used in part instead of herbicides, non-herbicidal alternatives are frequently used to make up for decreased herbicide efficacy brought on by an increase in resistance (Moss, 2019; Tahir *et al.*, 2024). Lower weed seed-banks combined with less herbicide usage are the key indicators of success for integrated water management (IWM). The increasing number and impact of herbicides resistance weeds population, the growing social pressure to reduce the use of pesticides in feed and food production systems from distinguished environmental and health viewpoints, and the rising costs, requirements, or restrictions surrounding pesticide registration and usage are all contributing factors to the combining of organic and conventional weed management strategies that we are already seeing. Due to the widespread presence of multiple-HR population in many major agricultural systems worldwide, will herbicides be a "once in a century" technique of controlling weeds (Davis and Frisvold, 2017; Arshad *et al*., 2024)? In the future, a crucial study question will be exactly how much weed control is necessary to reliably accomplish the low weed seed bank aim. This question suggests using less herbicide, as indicated by the herbicide loading (kg ha^{-1}) and the treated area multiplied by the number of applications. The economic viability, impact, and implications of reducing pesticide use can all be more effectively evaluated by applying standardised approach (Frisvold, 2019; Arshad *et al*., 2024a). Multi-site, medium-term (4–8 years) large-plot or landscape/field-level cultivation initiatives are needed to properly address this subject. It is possible to find more ecologically sustainable weed control mechanisms by comparing important agronomic, economic and environmental indicators across agricultural systems, each with its own crop series and combinations of weeds management strategies. Furthermore, in reduced-herbicide farming systems, weeds survey and related farmer management surveys can assist in identifying effective management strategies for preserving low weed seed banks (Hugh *et al.*, 2019).

5. Conclusion

Organic weed management in soybean cultivation presents both significant challenges and promising opportunities for sustainable agriculture. The comprehensive review of recent trends and methods highlights the efficacy of non-chemical weed control strategies, including preventive, cultural, mechanical, thermal, and biological approaches. Preventive measures such as high purity seeds and thorough cleaning of equipment are crucial for avoiding weed infestations. Cultural practices like narrow row spacing and high seeding density enhance crop competitiveness, while mechanical and thermal methods offer effective weed control without relying on chemicals. Although biological control methods are less prevalent, they provide environmentally friendly alternatives that could play a significant role in future weed management strategies. The review also underscores the ecological benefits of weeds, such as soil erosion reduction and soil structure improvement, emphasizing the importance of managing weeds as part of the agroecosystem rather than eliminating them entirely. However, the increasing herbicide resistance among weed populations necessitates a shift towards integrated weed management (IWM) strategies that combine conventional and organic practices. This integrated approach aims to reduce herbicide dependency, lower weed seed banks, and promote ecological balance. Looking forward, the future of weed management in soybean cultivation hinges on reducing herbicide use and integrating sustainable practices. The ongoing research and development of non-herbicidal alternatives, along with the merging of conventional and organic strategies, are critical for achieving sustainable soybean production. Long-term, multi-site studies are essential to identify the most effective and economically feasible weed management practices. By embracing these integrated approaches, farmers can enhance crop productivity, protect environmental health, and ensure the sustainability of soybean cultivation.

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