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Review

Non-Chemical Weed Control for Plant Health and Environment: Ecological Integrated Weed Management (EIWM)

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Abstract: Herbicide application has long been considered the most efficient weed control method in agricultural production worldwide. However, long-term use of agrochemicals has numerous negative effects on crops and the environment. Bearing in mind these negative impacts, the EU strategy for withdrawing many herbicides from use, and modern market demands for the production of healthy and safe food, there is a need for developing new effective, sustainable, and ecological weed control measures. To bring a fresh perspective on this topic, this paper aims to describe the most important non-chemical weed control strategies, including ecological integrated weed management (EIWM), limiting weed seed bank, site-specific weed management, mechanical weeding, mulching, crop competitiveness, intercropping, subsidiary crops, green manure, and bioherbicides.

Keywords: mechanical weeding; mulching; crop competitiveness; intercropping; subsidiary crops; green manure; bioherbicides

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1. Introduction

For decades, agriculture worldwide was fully reliant on herbicides as the most efficient and most effective weed control measure. However, long-term herbicide application has had a negative impact on the environment and human health, while simultaneously creating a global problem of herbicide resistance [1]. For this reason, Europe has defined thresholds for pesticide residues in water, food products, and soil through various acts of legislation, while also approving only a subset of active ingredients for use in weed control [2]. The goals of producing healthy and safe food, combined with the persistence of weeds and their tendency to develop different resistance mechanisms (resistance or tolerance to herbicides), have directed agriculture towards using non-chemical weed control measures.

Weed populations have developed different herbicide resistance mechanisms over time (target site, cross and multiple resistance, metabolism resistance, sequestration, etc.) [3–5]. As a result of this process, herbicide resistance has nowadays been recorded in 266 weed species (153 dicots and 113 monocots) on 21 out of 31 known modes of action, against 164 different herbicides, in 96 crops [6]. Other negative consequences of herbicide application reflect (1) directly on the environment (soil and groundwater pollution, accumulation of heavy metals) and (2) indirectly on human and animal health and welfare (development of different diseases, poor quality of life, unhealthy food, etc.). Science and practice have consequently been studying alternative weed control measures for years, by testing techniques which would ensure a cost–benefit balance in weed control. In general, diversity and density of weed species in synergy with different types of competition results in yield losses: up to 70% in soybean [7], 30–70% in maize [8], 20–70% in sunflower [9], 40% in wheat [10], and 18% in cotton [11].

Consequently, modern agricultural production requires a change in producers' awareness, in order to align with market demands and ensure a greater focus on improving the existing, and developing new, non-chemical methods for safe and successful weed control in agriculture [12] and ensuring a more precise ecological integrated weed management (EIWM) [13].

Bearing in mind the abovementioned, this paper presents alternative weed control measures which could successfully replace chemical weed control, while aligning with ecological principles. The aim of our paper is to shed light on all the available non-chemical weed management techniques, by analyzing their pros and cons and highlighting successful examples of their practical application. We begin by discussing the significance of EIWM (Section 1) and provide insights into the importance of managing the weed seed bank (Section 2) and discuss site-specific weed management strategies (Section 3). We emphasize the equal value of simultaneously controlling weed seeds, seedlings, and adult plants. Emphasis is placed on the application of different weed control methods, regardless of the characteristics and interactions in a crop–weed community. By analyzing the pros and cons of each individual technique, based on theory and practical experience, we propose an alternative vision for organizing organic food production (Section 4).

Contemporary Weed Management: Ecological Integrated Weed Management (EIWM)

Modern-day weed management practices aiming to protect crops from economic losses caused by weed infestations still rely on the traditional definition that each undesired plant/plant population in the selected crop field should be considered a weed. Although this definition is simple, weed control entails a thorough analysis and detailed planning based on scientific data and practical experience, aimed at developing EIWM [14]. Choosing an ideal combination of agrotechnical measures (IWM) is not easy because the damage caused by weed presence most often results from a synergy of multiple species. Furthermore, regardless of the applied measures (both preventative and curative), weeds occur each year, and their presence over several years is inevitable (due to the persistent seedbank). In general, EIWM aims to retain the advantage of crops over weeds throughout the season [15], by applying the existing (conventional/modern) management options in a progressive manner [16]. This implies the control of weed germination and reduction of weed density in crops, through the application of non-chemical techniques, with the aim of increasing the relative competitive ability of crops [17]. The end goal is achieving a long-term weed control strategy by decreasing the negative effects of agrochemicals (herbicides) on human health, the environment, weed resistance, weed shifts, spread of invasive weeds, etc.

2. Limiting Weed Seed Bank

In all agricultural production systems, limiting the weed seed bank is an important step in a successful weed control program. It is a nonspecific and elementary measure in every weed control strategy because it defines its direction, with the aim of successfully controlling aboveground weed infestations [18]. Techniques such as tillage fallow and false seedbeds manage the weed seedbank directly.

False seedbeds are a technique which initiates weed seed germination and their removal (hand-weeding, flaming, tillage, etc.) prior to sowing of crops. Crop germination and sprouting is facilitated in this manner, without disrupting the seed distribution in the seed bank, while at the same time reducing the potential for weediness during the season. This technique is grounded in the fact that 85–95% of seeds are dormant, while a small proportion of them (5–15%) germinate immediately [19], thereby ensuring the simplicity and success of this weed control technique. In combination with tillage fallow, a controlled and depleted weed seed bank is ensured, the weed abundance and diversity are reduced, and their further spread is prevented. Moreover, the soil is also aerated in this manner, thereby enhancing its microbiological activity. The main advantage of this technique is that it presents an alternative to herbicides, resulting in no environmental pollution and ensuring high yields of healthy and safe food, which is all in line with ecological weed management. If applied correctly (maximum cultivation depth of 5 cm), there are practically no drawbacks to either of the two techniques. Weather conditions and germination time of the crop are the only limiting factors [19].

Preventing new seeds setting in the soil, i.e., harvest weed seed control (HWSC) [20], is an indirect seed bank management technique. The technique itself can increase the capital investment in the production process and lead to potential side-effects (e.g., dust setting, hard working conditions in a harvester, fire hazard, etc.) which need to be resolved. Nevertheless, this technique is an excellent additional form of preventative seed bank control. While analyzing the efficacy of HWSC, Walsh et al. [20] observed the reduction and destruction of monocot weed seeds during the harvesting of cereals (e.g., 99% of seeds of *Bromus rigidus* Roth. and *Avena fatua* L., 95% *Lolium rigidum* Gaud. and 93% *Raphanus raphanistrum* L.) [21]. Moreover, Schwartz-Lazaro et al. [22] observed a similar degree of efficacy of HWSC during the harvesting of soybean. With minimal modifications, a harvest seed destructor achieved the control of some more harmful weed species (e.g., *Ipomoea lacunosa* L., *Xanthium strumarium* L., and *Amaranthus palmeri* S. Wats.).

3. Site-Specific Weed Management

A contemporary approach to weed control entails a reduction in investments and a more ecological approach to weed control activities. Site-specific weed management is a technique which is in line with these principles. It is based on following seedling emergence, determining critical zones in the field, and previous observations which must be accounted for each year [23]. Defining reliable activities within site-specific weed management is based on experience and selection of a single scouting strategy [23,24]. In general, site-specific weed management entails a symbiosis of the available commercial techniques of weed control and modern information technologies (IT), i.e., Global Positioning System (GPS) and Global Information System (GIS). Application of these IT systems in agriculture enables the producers to focus their previously uniform weed control measures into more targeted control actions [25–28]. Equipping different weed control machines with geolocating software ensures many advantages—human labor and fuel consumption are reduced, while achieving a good cost–benefit ratio between investments and crop yield [29]. Agricultural machines equipped with vision weed-sensing technologies enable a robotic method of weed control for reducing hand labor or excess herbicide application, with the end goal of achieving herbicide-free agricultural production [30]. Different agricultural machines are used for this purpose: tractor-mounted hoes with automatic guidance systems [31], weed chippers, camera-guided cultivators, rotary hoes, etc. Intra-row weed control machinery has proven to be very efficient in organic farming systems [32,33]. The machine detects differences between crops and weeds in crop rows using cameras and image processing software, and, following a signal, it is actuated into operation at the predetermined location [34]. Although a modern ecological approach to weed control entails non-chemical weed control methods, the spot-spraying form of site-specific weed management should also be considered. In the absence of alternative options for removing resilient (e.g., perennial) weeds, by carefully selecting bioherbicides or herbicides, and applying them only in selected locations, the application of these chemicals is reduced and well-controlled overall. In line with this, Gutjahr et al. [35] have shown that application of a multi-tank sprayer can retain up to 59–80% of the field as an untreated area. Site-specific weed management has potential for use in organic production systems, in crops where options for weed control are limited (e.g., medicinal herbs), and in intensive crops where using robots for weeding increases the speed of production [36]. The main caveat of a wider application of IT-equipped machines is the amount of investment needed for system purchase and maintenance, technical and informatic illiteracy of producers [37], and a lack of justification for such investments due to high weed abundance in the field [38].

4. Mechanical Weeding

Mechanical weeding is the basic method of weed control, associated with cultivation and tillage systems (hand hoeing, harrowing, rotary hoeing, and the use of rototillers and cultivators) [39,40]. The mechanical methods are effective for controlling larger weeds [41,42], as they have a higher impact on root-propagated weeds [41], bury the weeds and their seeds deep in the ground, so as to prevent germination [43], ensure advantage of crop seedlings [44], improve the soil moisture status and accessibility of decomposers to organic residues [45], etc. However, the main disadvantage of these techniques is that they are short-term, expensive (especially hand hoeing), and can potentially lead to mechanical damage of soil structure, e.g., rotary tiller and vertical power harrowing [43,46]. Due to all of the above, mechanical weeding should also be performed in rotation with other methods of weed removal.

4.1. Mulching

In general, using mulches in weed control can be beneficial on multiple levels, especially in high-yielding crops whose commercial prices are high or which do not have other acceptable control measures available (e.g., in the production of medicinal plants). Mulching enacts a direct mechanical pressure on weeds [47] and prevents or postpones their germination and emergence, thus providing crops with a competitive advantage, by creating favorable conditions for their development. Meanwhile, it indirectly regulates the soil pH and humidity, prevents temperature oscillations, and reduces pest and disease incidence [48]. Its efficiency depends on the type of the material used for mulching (organic or synthetic) and its thickness and durability during the application period. Moreover, mulching can also control herbicide-resistant weed populations by reducing their spread and seed dispersal. Application of natural (organic) mulches prevents seed germination, enriches the soil, improves its structure, and provides nutrients for the crop. An additional advantage of mulches is that it is not necessary to remove them from the surfaces where they have been applied, leading to no additional investments needed for their removal. Synthetic mulches can be biodegradable, and different types of PVC sheets are most often used. Compared to natural mulches (pine needles, sawdust, straw, compost), they are more efficient in weed control [49], despite increasing the production costs. Biodegradable and photodegradable materials used for mulching ensure better environmental protection and reduce the use of manual labor needed for their removal [50], making them more valuable in ecological weed management practices.

Living mulches (wheat, barley, legumes, perennial species in perennial plantations) are also often used in practice, as they are more practical for weed control. Their application is more acceptable for many reasons: they reduce weed presence, enrich the soil with nitrogen, improve soil structure, could be used as poultry and livestock fodder, and can also serve as silage [51]. Moreover, their application is also possible in row crops (maize, soybean, sunflower) and fields of medicinal plants [52]. The pros and cons of living mulches are often debated [53] from the standpoint of ideal species, which will not compete with the crop and impede it from reaching its full potential. Using mulches (biodegradable and/or living) ensures good weed control, greater microbiological soil activity, and better nutrient cycling and their absorption by crops, without requiring any additional investments [54]. Consequently, the environment remains unpolluted, and there is no danger of harmful elements entering the food cycle of either the animal or human populations. On the other hand, one must also consider the fact that living mulches (plant residue) can contain weed seeds and sources of pathogens while synthetic mulches are more durable and efficient but increase the production cost [55]. A question also remains whether mulches will have any future negative long-term effects. Therefore, mulches in weed control should only be seen as part of the weed management system, used in rotation with other nonchemical weed control methods.

4.2. Flaming

Flaming is an old and well-known non-chemical weed control method. The first practical experiences in flaming are mentioned as early as the 1930s. However, production of selective herbicides and fuel costs have resulted in the abandonment of this practice for a period of 20 years [56]. The interest for flaming as a weed control method has seen a comeback lately due to prioritizing organic over conventional farming [57] and aiming to produce safe and healthy food. Different types of flaming used (pre-em flaming, between-row and in-row crops flaming, and flaming after crop sprouting) depend on several factors: quantity of propane needed, speed of movement of the machine, crop sensitivity, angle under which the burner should be set against the crop, etc. [58]. Pre-em flaming (seedbed sterilization) can be combined with the direct weed seed bank control technique. It is often applied just prior to crop emergence to give the crop a good weed-free start. A somewhat more specific flaming method is after crop sprouting when both the crop and weeds are burned. This method can be used in those crops which can resprout after flaming, due to the protected vegetation cone [59]. The most common practical weeding application is in-row and between-row flaming [60,61]. The results have shown that higher efficacy is achieved when controlling dicot weed species [62], but weeds are generally more successfully controlled in earlier growth, especially species with an open vegetation growth point, such as *Capsella bursa-pastoris* (L.) Medic. and *Chamomilla suaveolens* (Pursh) Rydb. Nevertheless, experience has shown that some economically harmful weed species (*Ambrosia artemisiifolia* L., *X. strumarium*, *Sorghum halepense* (L.) Pers., etc.) are more difficult to control in this manner [63,64]. In general, the technology itself is safe for the crops, although damage may occur on lower leaves, especially in early growth stages. How much and how fast the crops will recover depends primarily on the quantity of propane used while flaming [65]. Furthermore, the safety of flaming as a weed control measure depends on the crop and its growth stages. Therefore, flaming as a weed control method has not become so well-established in agricultural production, but remains a highly acceptable option for weed control in perennial crops, potato desiccation, and in urban green areas [40], as well as in organic agriculture [66]. The drawback of this technology is that efficacy is reduced in extremely abundant weed populations (because plants which grow in dense stands cover each other) and its very high fossil fuel consumption, resulting in energy inefficiency [67].

4.3. Crop Competitiveness

An important aspect of EIWM systems is increasing the competitive ability of crops, as part of alternative (non-chemical) and ecologically acceptable weed control methods [12,68]. The competitive ability of crops is associated with their early emergence, rapid leaf expansion, dense canopy, increased plant height, and early growth of a vigorous root/shoot system [69,70]. The duration of competitive interactions determines the final losses in the growth and development of the plant, and therefore in the crop yield. Planting competitive cultivars at relatively high seeding rates, with controlled application of fertilizers (subsurface banded or point-injected nitrogen), could reduce the negative impacts of weeds on the crop and the amount of weed seeds in the seed bank [68,71]. Cultivars may vary in their competitiveness because weeds reduce the water and nutrient content in the soil profile, making this resource less available, leading the crops into a state of stress, slowing down their growth and development and finally reducing their yield [72]. Although a continued crop cultivation and weed control are needed for achieving high yields, each crop species has specific development stages during the vegetation season (maize 3–5, soybean 2–4, rice 4–6 weeks after planting) when it is desirable to remove all weed pressures (critical period of weed control). Knowing the critical period of weed control in each crop can be seen as the starting point when planning weed management [73]. Crop competitiveness could represent a leading tool in plant production, while modern tendencies (preventing global warming, environmental protection, etc.) activate individual components of this dynamic system (sowing date, pre-sowing treatments, cultivation, nutrient content) and define the agrotechnical measures needed for weed control in EIWM (flaming, herbicide use, mulching, etc.).

4.4. Intercropping

Intercropping is another element of EIWM. It consists of sowing/growing multiple crops simultaneously on the same field, with the aim of achieving higher yields [74]. Intercropping ensures a balance with regards to nutrient, light, water, space requirement of crops, and their allelopathic interactions [75], which is achieved by removing the specifically adapted weed species without using herbicides, to preserve the environment. Intercropping can be performed in several ways: by simply mixing two annual crops (wheat with clover/bean), by using alternate rows (simultaneous growing of soybean and maize), by sowing a second crop after the first one has flowered or just before its harvest, and by growing woody vegetation with annual crops [76]. Crops are selected meticulously, to ensure that they ensure a twofold harvest/yield, achieve successful weed control, without needing to apply either chemical or non-chemical measures, increase the diversity of soil microorganisms, prevent soil erosion [77], increase light capture [78], reduce the competitive advantage of weeds (physical presence, allelopathy [79], increase nutrient availability [80], and do not compete with each other. The most important aspect of intercropping, regardless of increased management complexity, is to ensure high yields [81]. This form of cultivation, with good crop selection, can increase the fitness of one or both plants (the taller plant protects the shorter one from wind or excess light; root mycorrhizae of one species increases nitrogen availability to the other, reduces disease incidence, etc.) [82–85]. In general, intercropping systems are becoming increasingly important in ecological weed management.

4.5. Subsidiary/Cover Crops

Subsidiary/cover crops are a weed control strategy conducted off-season in order to cover the field surface and ensure sufficient nutrition for the following season. Any crop can be a subsidiary crop. However, there are certain plants which are especially efficient (grasses, legumes) in covering the soil, producing nutrients, and fixating carbon and nitrogen from the atmosphere, with minimal activity of the producer [86]. Cover crops are sown in the autumn months and mown in the spring (for use as silage), left on the soil surface, or plowed in [87]. Some favorable properties of cover crops are that they have rapid germination and seedling development, vigorous seedlings, good tolerance to changing weather conditions, can be easily removed, and maintained, are good competitors, etc. [88]. Despite the success of subsidiary crops regarding economic factors and variety of environmental conditions [89], there is a vision for using cover/subsidiary crops on a million acres of land in the future.

4.6. Green Manure

Green manure represents a crop which is primarily used as a nutrient source and soil amendment [90]. Green manure can be used as a weed control technique during the vegetation season, in rotation with other agrotechnical measures (mulching, crop rotation, intercropping and composting). Its application aims to improve the physical, chemical, and nutritive properties of the soil, bring nutrients back to the soil, and improve the soil quality and its microbial activity [91,92], while also reducing the pest incidence [93] and weed density. Green manure ensures successful weed control through allelopathy and by outcompeting (for space, light, etc.) weed species. One of its successful examples is placing *Eucalyptus globulus* Labill. leaves between maize plants, thereby preventing weed germination of *Amaranthus retroflexus* L. and *Solanum nigrum* L. [94]. Another advantage of plowing down green manure is that it prolongs the effects of allelochemicals on weeds (e.g., reducing the spread of grass weeds *Echinochloa crus-galli* L. and *Digitaria sanguinalis* L. Scop by approximately 94% and 80%, respectively), while organic matter decomposition increases crop yields (e.g., of maize by 37%) [94]. Green manure plants (wheat, barley, legume plants) can be a single species or a mixture of species (good for silage).

In general, the technique of green manure can imply leaving plant residue on the soil surface, to act as natural fertilizers. Additionally, this technique reduces pollution by minimizing the need for other agrotechnical measures: fungicides and nematicides [95], fertilizers [96], etc. Inadequate use of this technique (not choosing the sowing time adequately, not choosing the green manure species wisely) can disrupt the development of the main crop. Often, the wrong choice of green manure can complicate fruit yielding of the main crop (common use of legumes leads to a surplus of nitrogen in the soil) and disrupt the sowing of the main crop in the rotation system (cabbage, cauliflower, or broccoli vs. mustard). In addition, improper care can rob the crop of nutrients, e.g., by allowing the green manure plants to flower [97]. Although there are pros and cons for use of green manure, there will often be a dilemma for how to find the balance between the investments (finances, steps of the production process) and ensure that healthy and safe food is produced as part of the ecological (organic) weed management.

4.7. Bioherbicides, as Part of the Biological Weed Control System

From the standpoint of both science and agricultural practice, the most promising technique in the non-chemical (ecological) weed control is the application of natural weed control products. It is especially promising in dealing with the weed resistance problem. Although studied from the beginning of the 20th century, a list of registered pathogens for use as bioherbicides dates back to the 1980s [98], and over 100 bacterial and fungal agents have now been evaluated to serve as bioherbicides [99]. Biocontrol of weeds *sensu lato* includes several possible avenues: classical (using a non-native organism), inundative (rearing an organism in a controlled setting then releasing), and conservation (manipulating a cropping system to increase the populations of natural weed-suppressing organisms) [100]. Strictly speaking, biocontrol implies the use of organic products in weed control (phytotoxins, pathogens, fungi, and bacteria) [101,102]. However, the efficacy of bioherbicides as a non-chemical weed control measure mostly relies on laboratory studies, as its practical application has only started in a limited number of small field sites [103]. Regardless of its limited application, bioherbicides have a number of advantages as an alternative to herbicides: control of weed seed germination and growth, no pollution, environmentally friendly, user safety, low risk of development of resistance, etc. [102,104,105]. Nevertheless, there are still dilemmas on how to create a product which would be efficient, stable, ecologically friendly, and with no long-term side-effects. Organic food producers are highly interested in such solutions, which would enable them to fully align their production with the principles of EIWM.

5. Conclusions

Following recommendations given in the EU Directive on the sustainable use of pesticides [2], many herbicides have been withdrawn from use in the EU and some other countries. Non-chemical methods, such as limiting weed seed bank, site-specific weed management, weed control by mechanical operations, mulching, flaming, crop–weed interaction, intercropping, subsidiary crops, and green manure, although all less efficient when compared with herbicides [106], will be necessary for EIWM. Although they may not be well accepted as individual methods of weed control, in combination with other agrotechnical measures, they could ensure a systematic way to provide sustainable and reliable weed control, especially in organic production and in small farming systems. Long-term weed control must be simple, flexible, safe, and efficient, while at the same time incorporated in EIWM practices, which will depend on the diversity and density of weeds.

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