WEED CONTROL IN ORGANIC FARMING

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SUMMARY

Over the past few years, both producers and consumers have become increasingly interested in organic farming because conventional agriculture relies so heavily on the use of synthetic pesticides, thus causing environmental pollution. Weeds, as inevitable "companions" of cultivated plants, represent a major, everlasting issue in plant production. As organic plant production is legally regulated, the control of undesirable plants such as weeds is further complicated. Using the relevant literature, the purpose of this study is to survey the existing weed control methods in organic crop production. In order to be certified, organic plants have to be grown in the farming system without the application of synthetic herbicides and other chemicals that are commonly used in conventional production. This means that crop growers have to apply non-chemical, alternative methods of weed suppression, i.e. weed control based on the combination of cropping practices, mechanical control, and the use of bioherbicides. There is a large number of plant extracts with bioherbicidal activity, the effect of which is mostly attributed to the biological phenomenon of allelopathy, rendering such weed control sustainable, inexpensive, and environmentally friendly. Although bioherbicides are successfully used in organic farming worldwide, there are no registered bioherbicides in Serbia to date (according to the data of the Ministry of Agriculture, Forestry and Water Management of the Republic of Serbia). Both organic producers and experts should raise awareness of the importance of successful weed control to the health of cultivated plants, soil, beneficial organisms, and the entire ecosystem, which requires further research attention.

Key words: organic agriculture, weed control, cropping practices, bioherbicides

INTRODUCTION

Areas devoted to organic farming and organic food markets have been expanding worldwide (Golijan & Dimitrijević, 2018). The methods of organic farming are legally regulated, thus certified organic food is labelled as an organic product (Golijan & Sečanski, 2021). Weed control is one of the most serious challenges farmers have to face when converting from conventional to organic production. In organic production, the control of diseases, pests and weeds is the most pressing issue because the use of synthetic chemical preparations applied in conventional agriculture is not allowed (Golijan & Sečanski, 2022). In order to be labelled as an organic product, an agricultural product has to be cultivated without the use of any chemical preparations. Moreover, organic farmers are not allowed to apply chemical methods in weed suppression. The control methods alternative to chemical can be physical, cultural or biological (Stockdale et al., 2001). In successful weed control, it is necessary to suppress unwanted...
vegetation and promote the growth of desirable crops. One of the best means to eradicate weeds is a robust plant stand. Various weed species occur in different times during the year, or appear in different crops. Some weed control methods such as the disking of a field overgrown with couch grass can accelerate the predominance of specific weed species in particular environments. Grassy weeds frequently need control methods that are not usually required by broad-leaved weeds. A proper identification of weed species in the field is a crucial factor of selecting and timing the effective measures of weed suppression (Howell & Martens, 2022). The optimal weed control strategy is frequently determined by the weed life cycle (annual, biennial or perennial). Weed seeds respond to light, humidity and temperature, i.e. weed seeds whose life cycle ends in autumn germinate in a warm soil (Anonymous, 2022). The largest number of organic pesticides is made from chemicals that occur in nature. A phenomenon that one plant species produces biological chemicals that affect, positively or negatively, the neighbouring plant species is called allelopathy (Cheng & Cheng, 2015). Some weeds and crops can discharge chemical substances by the processes of exudation, leaching, and volatilisation, or by the decomposition of their tissues into the surroundings. When these biochemicals (allelochemicals) come in contact with other plants, they either prevent or promote their development. The persistence of allelochemicals in the soil can be enduring, affecting the following crop in rotation (Webber et al., 2012).

The fertility and texture of the soil in the organic farming system mainly depend on the soil biological activity. A dynamic and diverse microbial population in the soil is very important for the growth of healthy, high-yielding organic crops. In the organic farming system, long-term fertilized soils supply plants with nutrients. The adequate equilibrium of fundamental nutrients can often diminish weed issues and improve the growth and development of crops. A number of organic farmers use manure incorrectly, or they use unprepared manure. This can disturb the balance of nutrients and microbes in the soil, leading to an increase in weed growth. The soil looseness and tilth can be increased with soil fertility amendments such as gypsum. This can contribute to the success of mechanised cropping practices and diminish the pressure from weeds that prefer hard, compact soils (Howell & Martens, 2022). This paper presents a survey of the most important weed control methods in organic farming.

PHYSICAL WEED CONTROL

Physical weed control refers to weed removal by hand, machinery and equipment, or thermal methods (Stockdale et al., 2001).

Mechanical weed control

Tillage. Tillage is frequently required for the removal of established weeds, particularly perennial weeds that grow from vegetative parts such as storage roots, rhizomes, or other underground structures. Tillage encompasses the uprooting of weeds and the chopping of weed shoots and roots. It also includes the burying of weeds and their seeds, or a combination of all these practices depending on the tool(s) used. As the majority of tillage practices successfully remove established weeds, their effects on seeds (both on the plant and in the soil) can vary from the total reduction to a great enhancement of subsequent seed emergence. Tillage can speed up seed germination by scarification (nicking, breaking, scratching...), i.e. seed exposure to a brief flash of light. Furthermore, the soil is loosened, aerated, mineralised and dried by the upward and downward movements of seeds caused by tillage. These alternations to soil conditions can result in seed germination or seed dormancy. Weed species and their life stages differ, thus respond differently to mechanical control. Therefore, the weeds present have to be considered when selecting the time of and tools for primary and secondary tillage. Primary tillage implements encompass mouldboard (turn) ploughs, chisel ploughs, disc ploughs, rotary spaders, and rotary tillers. Secondary tillage implements encompass disc harrows, field cultivators, spring-tooth harrows, spike-tooth harrows, and rotary tillers (Schonbeck, 2019).

It is important to emphasise that the effectiveness of tillage in weed control greatly depends on weather conditions. The tillage performed on a hot, sunny day provides the best weed control as noxious weeds with long underground rhizomes (such as couch grass) can be pulled out and left to shrivel. If a wet soil is tilled, the soil will compact and its texture will be lost, which will then favour weed species with a preference for hard soils and aggravate subsequent crop growing. If wet weather occurs after tillage, weeds can root again. If initial tillage is followed by cold, wet conditions, the germination of weed seeds can be inhibited and the effect of stale seedbed can be reduced. Soil aeration is also of great importance, particularly in the organic production system depending on the activity of microbes for sustainable crop growing. When new oxygen is introduced, microbes living in the soil transform organic matter into stable humus. They also reproduce, releasing easy accessible nutrients into the soil solution, which is then used by crops (Howell & Martens, 2022).
**Blind cultivation.** Due to differences in the height of the crop and the weed, blind cultivation is the simplest and most effective mechanical weed control method. This method refers to cultivating fields with no regard to the placement of the field rows. The purpose of blind cultivation is to dislodge shallow-rooted weeds in the 2-5-cm topsoil, causing considerable number of small size weed seeds (that are in the process of germination) to completely dry and wilt. Since large seeds of crops germinate below the sowing depth, blind cultivation does not cause any damage to them. Blind cultivation can break a soil crust, and thus allow the emergence of crop seedlings. Implements for precise weed suppression and control can be dragged across the field at relatively high speeds (5 to 10 km/h), regardless of the row location (Howell & Martens, 2022).

**Inter-row cultivation.** The good time to start inter-row cultivation is when the crop rows are easily observable, i.e. maize plants are 20-25 cm in height and soybeans are in the third trifoliate stage. If a good size differential between the crops and weeds has not be achieved, earlier cultivation may be required, particularly if weather conditions have prevented early season weed-control operations to be performed optimally. However, weed growing will be less vigorous and aggressive provided the valuable plants are tall enough not to be buried with weeds. The first pass is crucial to determine the seasonal weed control, but the second one is commonly needed for the elimination of weeds whose growth was stimulated by the first cultivation, and for further aeration of the soil (Howell & Martens, 2022). According to Sarker et al. (2002), weed densities reduced with the increase in multiple rice production systems. Owing to weed removal in all locations, the total density of weeds was decreased 32 days after transplanting (DAT). Different weed classes respond differently to inter-row cultivation. Based on the study carried out by Haden et al. (2007), inter-row cultivation reduced the number of different species at 32 DAT. Following the period of 32 DAT, the number of weed species in the treated weed population was smaller, and the overall diversity was lower than in the untreated weed population. Intensive inter-row cultivation (twice with both a rotary hoe and a wooden weeder) was found an efficient, but difficult strategy for weed suppression. All the weed classes considered responded satisfactorily to this weeding treatment.

**Thermal weeding methods**

Thermal weeding methods can be classified into two groups: high-temperature and low-temperature weeding methods. High-temperature weeding methods include hot water or steam (HW), infrared radiation (IR), open flame (OF), and microwave radiation, whereas low-temperature weeding methods entail liquid nitrogen. HW, IR and OF have been used in crop cultivation, glasshouses, public gardens, and schoolyards. HW is applied directly to the weeds, and there is no fire risk because there is no flame. HW can be applied under varying weather conditions such as windy or rainy conditions with no concern for soil drifting, surface runoff, or loss of efficacy (Stockdale et al., 2001).

A number of farmers use propane flame burners in vegetable growing, either backpack or tractor-mounted flame weeder, to destroy small weeds immediately before cropping. The entire fields are flamed with this equipment. Farmers who use propane flame weeding between crop rows install special heatproof shields for crop protection. Organic farmers often burn a stale seedbed to eliminate young weeds without disturbing the soil. It is done immediately before or immediately after crop sowing. These tools have flame hoods or shields that aim the heat at the target weeds, and are therefore more energy efficient (Schonbeck, 2019). Flaming can be a pre-emergence approach to suppressing the emergence of broadleaf weeds, which is less expensive and more efficient than hand-pulling (Anonymous, 2022). According to Diver (2002), flaming is most efficient and energy-saving when used on weeds not higher than 5 cm. If the OF method is applied with flames at temperatures of up to 1000°C to plant leaf area for at least 0.1 s, the internal water located within cells boils and cell membranes burst leading to dehydration and death (Lague et al., 2001). Not many crops are tolerant to flaming between rows at certain stages of their development. However, maize, onions and cotton are such crops; growth points of several-cm tall maize and onion plants are protected by the internal structure of the plants, whereas cotton ligneous stem is fairly flame resistant. The flame directed to the soil surface from both sides of the row is intended to shortly expose weeds to intense heat, so that cell membranes will burst and cause the weed to desiccate and die soon (Diver, 2002; Schonbeck, 2019). OF is more effective for suppressing broadleaf species than other weed species (Litterick et al., 1999). Even though OF can be used for the majority of crops, it is not recommended for shallow-rooted crops (Bond & Grundy, 2001).

Steam weeder, hot water and infrared heaters are also used in thermal weeding. Infrared weeder use propane metal or ceramic plates to radiate heat on weed tops. Although the effects of infrared weeder are positive, their energy requirement is much higher than that of flame weeder (Astatkie et al., 2007). The adequate exposure time is necessary for IR radiation to be successful in weed eradication (Bond & Grundy, 2001; Lague et al., 2001).
comparison to HW, an area covered by an IR thermal unit is clearly determined, thus injuries and damages to the crop are reduced.

Aasc (1998) set up field experiments to examine the efficiency of a propane flamer and an infrared radiator in a weeded white mustard field. A better performance was achieved by the flamer when used on 4-leaf stage plants, whereas the radiator proved more efficient with plants in the cotyledon stage.

CROPPING PRACTICES

Cover crops

Cover crops are crops that provide soil protection by slowing erosion and improving the soil health status between periods of crop cultivation or among trees in orchards and vines in vineyards. These crops are not grown for market purposes, but they are incorporated into the soil when breaking through the plough pan. They may also be used as green manure crops. Growing cover crops prior to or between full-season crops and among trees or bushes of fruits and vine can result in better physical, chemical, and biological properties of the soil, which can consequently improve the soil health and increase the yield of valuable crops. If mulched in the no-till farming system, cover crops can increase nitrogen economy and conserve the soil retention of moisture and organic matter. It can also decrease soil erosion, enhance soil physical traits and soil fertility, suppress weeds, reduce diseases and pests, reduce global warming, and improve crop yields (Fageria et al., 2005).

The role of cover crops in supporting soil function is even more important in organic farming as the application of synthetic chemical fertilisers and pesticides is forbidden. The main concern when selecting a cover crop is the purpose and objective of its use. Accordingly, the following factors are to be considered: seed availability, cost, crop rotation, and sowing and incorporation machinery (Dufour et al., 2014).

Cover crop mixes, often referred to as combinations, can provide high-quality residues, and their carbon-to-nitrogen ratio facilitates cover crop growing (Treadwell et al., 2010). Furthermore, they can improve soil cover, weed destruction, and biomass, particularly under arid and other unfavourable conditions (Stika, 2013). A further benefit of sowing cover crop mixes, or rotating cover crops, is reflected in decreasing plant pathogens or soil parasitic nematodes.

Instead of leaving arable land without sowing, annual or short-term perennial cover crops, which develop quickly and overlap weeds before they have the chance to emerge, could be sown weed control. For example, if commercial crop sowing is planned for early spring, winter annual cover crops such as a mixture of oats and crimson clover that die back early could be selected for sowing. If late spring and early summer commercial crops are to be sown, cover crops that can overwinter well, such as hairy vetch and rye, could be used. Annual cover crops can be used as mulch or could be roll-crimped, or just left to die naturally (Anonymous, 2022). The biological N fixation by legume plants can decrease the needs for N fertilisers in the succeeding crop (Singh et al., 2004). The bioculture of grass and legume was used to show that the N release from biocultures was reduced when compared to legume continuous cropping.

Mulching

According to numerous studies, organic mulch materials raise the level of soil nutrients, maintain the optimal soil temperature, limit the rate of evaporation from the soil surface, hamper weed growth, improve soil health, and prevent soil erosion. There are many types of materials that can be used to cover the soil surface: straw free of noxious weeds, thick layers of leaf mulch, well-composted manure, and mulch materials such as natural, synthetic, petroleum, conventional, inorganic and organic mulches (Anonymous, 2022). These materials are commonly grouped into organic and inorganic mulch materials. There are several types of organic mulches: wood bark, wood chip, grass clippings, hay, straw, shredded leaves, etc. As weed seeds need moisture and light to germinate, mulching can keep seeds in the dark, thus inhibiting their growth. Mulches can provide protection for ground beetles and other beneficial predators that feed on weed seeds. They also retain moisture in the soil, which is necessary for crop production, maintain soil suitability for sowing and growing crops, prevent surface crusting, provide food for all organisms living on or in the soil, and sometimes provide slow-release nutrients. An 8-10 cm hay or straw mulch can successfully decrease the emergence of broadleaf weed seedlings (Schonbeck, 2019).

Living mulch, i.e. any plant covering certain area during the entire season, can suppress early season weed seed germination, provide the equilibrium between crops and weeds, and ensure the crop’s access to light, water, and

46
nutrients. The timing of living mulch in weed suppression is vital for obtaining adequate crop yields (Leary & DeFrank, 2000). According to Paine & Harrison (1993), the following properties are important for living mulch species: the rapid establishment for early weed suppression and soil erosion prevention, adequate wear tolerance and persistence, drought tolerance and low fertility, and low maintenance budget relative to mowing intervals, fertiliser needs, cover removal, or chemical mowing.

**Bark.** Bark mulch or chippings are good materials because they contain and retain moisture for longer periods, which facilitates crop growing. It is usually used for plant beds, borders and landscaping, but it should not be used in vegetable fields because it contributes to soil acidification (Ranjan et al., 2017).

**Grass clipping.** Mulching using the organic material such as straw or grass clippings has become very popular in growing vegetables and annual flowers. Certain mulch material, including grass clippings, may also fertilise the crop. Furthermore, mulching evens out or lowers average soil temperatures (Hellqvist, 1996). Freshly mowed grass clippings should not be removed from the field because they degrade easily and increase the nitrogen levels in the soil. If they are applied in thin layers, grass clippings make a good mulch, especially if they are left to dry between applications. As they decompose rapidly, additional layers during the growing season are desirable. A grass clipping mulch recycles its nutrients into the garden bed (Whiting et al., 2015).

**Straw.** Straw is an ideal mulching material because it is easily applied in the field, remains in place, and reflects sunlight, which improves fruit bearing in some vegetables. It is used as both winter protection and summer mulch in vegetable fields because of its weed seed free property. The thickness of the applied straw mulch should be about 15-20 cm (Pedda Ghouse Peera et al., 2020).

**Black plastic film mulch.** A black plastic film mulch successfully obstructs the emergence of most weeds, including perennials. This type of mulch also eliminates the light stimulus for weed seed germination. Nevertheless, such synthetic materials do not improve soil quality, can obstruct rain penetration, and (unless biodegradable) require removal and discarding at the end of the season. Additionally, weeds often penetrate sowing holes, where their control is very challenging. Weed barriers (perforated materials) are also used. They last several seasons and can be remarkably useful in establishing perennial crops. Paper mulches are less effective than plastic, but if used beneath hay or any other organic mulch, can suppress weeds more than the organic mulch alone. Transparent plastic mulches warm up the soil much more than black plastic mulches. During hot summer weather, they can affect the exposure of the soil to sunrays (solarisation), which is yet another form of thermal weeding. Solarisation eradicates emerging weeds, certain soil-borne crop pathogens, insect pests, and even some weed seeds and vegetative propagules of perennial weeds. Conversely, if weather conditions are cold or cloudy, they will not support effective solarisation, but will just accelerate weed development under the plastic film by creating approximately optimum temperatures (Feeser et al., 2014).

**Compost**

As a process that converts organic materials into mulch through natural decomposition, composting is preferred over organic waste, which is reduced to organic fertilisers and soil conditioners through biological processes (Gautam et al., 2010). During the composting process, different indicators such as the C:N ratio, composting temperature, pH of the end product, moisture content, and presence of potential pathogens such as coliform bacteria are used to estimate the quality and stability of the compost (Sanmanee et al., 2011).

The use of compost in vegetable fields should be minimised because the level of its nitrogen is too high. It may also contain weed seeds. Compost is best used for soil preparation or thin surface fertilisation early in the season. It can also be used as mulch in some plants such as roses. In such cases, mulch should be applied at a depth of 8-10 cm (Ranjan et al., 2017). Compost can efficiently control some soil-borne diseases, particularly root-rot diseases. If a favourable environment and food source are provided, compost supports the growth of microorganisms that compete with parasites, or produce natural antibiotics against plant pathogens. Furthermore, a great plant vigour caused by applied compost can increase the plant’s tolerance to pathogens. The quality of compost differs according to the raw organic materials (feedstocks) used, the composting process used, and the state of biological activity. Prior to the application as a soil amendment, the quality of compost should be evaluated relative to its moisture and organic matters, C:N ratio, and pH (Tab. 1) (Marriott & Zaborski, 2022).
The composting process consisted of three stages, using diverse microflora such as bacteria, fungi, and mesophilic (*Streptomyces rectus*) and thermophilic *Actinomycetes* (*Actinobifida chromogena* (*Thermomonomospora fusca*), *Microbispora* (*Thermopolyspora*) *bispora*, *Therinomnonospora curvata*, *Thermoactinomyces* sp. In due course, organic waste is converted to humus (Zeng et al., 2011). During the first stage, carbon dioxide and the temperature increase. The substrate is reduced, because mesophilic organisms degrade sugar and proteins. During the second stage, the temperature in the compost pile rises from 45 °C to approximately 70 °C, and thermophiles replace mesophiles. The third stage starts with the reduction in the temperature of the compost pile (Pan et al., 2012).

**Crop rotation**

Crop rotation is one of the most enduring and efficient methods of controlling pathogens found both in the soil and plant hosts. It also maintains soil fertility and texture. Without a good crop rotation, there is no organic weed control (Houben et al., 2020). It is recommendable to rotate pulses with grasses, crops in spring with crops sown in autumn, inter-tilled crops with close-sown crops, heavy feeders with light feeders. The appropriate use of cover crops in the bare soil surface increases beneficial nutrients (principally nitrogen), organic substances, diversity of various soil microbes, and soil erosion protection (Howell & Martens, 2022). When planning crop production, farmers should come up with a crop sequence for each field, considering the potential weed threat. Fast-growing crops that are able to prevail over weeds (namely winter squash, potatoes, sweet maize and tomatoes) are a good choice for the rotation (Anonymous, 2022).

Crop rotation in organic farming plays a significant role in reducing the damage of a great number of insects, pathogens, weeds, and plant diseases. The continuous cropping of the same plant family has to be avoided at all costs. For example, the *Brassicaceae* family (cole crops) should be sown prior to the *Asteraceae* family (lettuce, cut flowers). The *Solanaceae* family (tomatoes, potatoes, peppers, eggplants) should be grown after the *Asteraceae* family, whereas the *Curbitaceae* family (squashes, cucumbers, melons) should follow the *Asteraceae* family. In order to decide on the length of the rotation before re-sowing the same vegetable crop, it is of utmost importance to know how long the pathogens transmitted by or in the soil are able to survive in the field. In spite of certain exemptions, a rotation lasting four years, which encompasses a sequence of crops not prone to the same causative organisms, will generally minimise troubles caused by soil-borne diseases. This strategy will be efficient if weeds susceptible to pathogens and volunteer plants are also prevented from being in the field. Finger-and-toe disease on crucifers, sclerotinia white mould on lettuce, and fusarium wilt (a disease affecting variety of hosts including vegetables) differ from the rest of diseases (Baldwin, 2012). Table 2 shows an example of rotation periods to reduce soil-borne diseases.
Table 2. Rotation periods to reduce soil-borne diseases

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Disease</th>
<th>Years without a Susceptible Crop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asparagus</td>
<td>Fusarium rot</td>
<td>8</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Clubroot</td>
<td>7</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Blackleg</td>
<td>3-4</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Black rot</td>
<td>2-3</td>
</tr>
<tr>
<td>Muskemelon</td>
<td>Fusarium wilt</td>
<td>5</td>
</tr>
<tr>
<td>Parsnip</td>
<td>Root canker</td>
<td>2</td>
</tr>
<tr>
<td>Peas</td>
<td>Root rots</td>
<td>3-4</td>
</tr>
<tr>
<td>Peas</td>
<td>Fusarium wilt</td>
<td>5</td>
</tr>
<tr>
<td>Pumpkin</td>
<td>Black rot</td>
<td>2</td>
</tr>
<tr>
<td>Radish</td>
<td>Clubroot</td>
<td>7</td>
</tr>
</tbody>
</table>

Source: Baldwin (2012)

BIOHERBICIDES

Fungi are most often mentioned as bioherbicides, but there are numerous plant extracts exhibiting bioherbicial activity. This activity is mainly attributed to the phenomenon of allelopathy, due to which the method of applying bioherbicides is sustainable, inexpensive and environmentally friendly (Pacanoski, 2015). A small number of products are made to be used by organic growers in weed suppression (Schonbeck, 2019). These bioherbicides are successfully used in small weed control and short annuals. Substitute products for controlling weeds contain oils, soaps, acids, or iron compounds. The effects of all of these products are similar: leaf cuticles are damaged and leaf cells are destroyed, resulting in leaf death. These so-called burn-down herbicides act very quickly, but their effects depend on good coverage. Several bioherbicides derived from particular fungi were made to control certain weeds, especially those that were troublesome in certain locations. Weeds with large and deep roots and subterranean structures, broadleaf perennials and grassy weeds are successfully suppressed only by broad-spectrum herbicides (Koski, 2018). The application of salt water proved to be very successful only in the destruction of annual weeds. When using any herbicide, including bioherbicide, human safety always comes first. For instance, if the eye is exposed to vinegar with the concentration of acetic acid over 10%, a person can go blind (Webber et al., 2012).

According to the data of the Ministry of Agriculture, Forestry and Water Management of the Republic of Serbia, there are no registered bioherbicides in Serbia to date (Anonymous, 2021).

Allelopathy

Certain plant species produce chemical substances and release them from their roots to compete with neighbouring plants by inhibiting their growth. This phenomenon is known as allelopathy. Plants in nature can become dominant thanks to allelopathy. Growing allelopathic crops can be effective in intensely weed-infested fields as they can reduce total weed pressure. Allelopathic crops encompass the following plant species: barley, rye, annual ryegrass, buckwheat, oats, sorghum, Sudan-sorghum hybrids, alfalfa, wheat, red clover, and sunflower (Howell & Martens, 2022).

Allelochemicals inhibit the plant growth and development because they can affect nutrition by reducing mineral intake, the chlorophyll content (such as juglone), carbon flow, phytohormone activity, enzyme activity and production, etc. They can be found in different plant parts, particularly in leaves, roots, seeds, rhizomes and stems (they can also be detected in flowers, but in limited quantities). The emitter is a plant that emits allelochemicals into the environment, whereas the recipient is a plant affected by the substances released. When synthesising allelochemicals, temperature, light intensity and photoperiod play a crucial role, whereas the reduction in environmental humidity is also a significant factor for their activation (Vuković & Šunjka, 2021). It is assumed that allelopathy is conditioned by the mutual action of several allelochemicals with different sites of action in the cell (Zimdahl, 2018). Plants differ according to their allelopathic properties and susceptibility to allelochemicals produced by other crops. Therefore, seed germination of broadleaf weeds may be inhibited in the spring, following the ploughing-down of a winter cereal-rye cover crop, but sweet maize sown into that stubble may not be affected at all. Residues and leachates of certain crops also suppress weeds. Moreover, cover crops destroyed and left on the ground continue to suppress weeds, primarily by blocking sunlight (Baldwin, 2012). Table 3 presents certain plants with allelopathic action and susceptible weed species (Soltys et al., 2013).
Table 3. List of certain plants with allelopathic action and susceptible weed species

<table>
<thead>
<tr>
<th>Plants</th>
<th>Allelopathic action</th>
<th>Susceptible weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raphanus sativus</td>
<td>glucosinolates, isothiocyanates</td>
<td>Sonchus asper, Matricaria inodora, Amaranthus hybridus, Convolvulus arvensis, Capsella bursa-pastoris, Cuscuta spp., Daucus carota, Hirschefeldia incana</td>
</tr>
<tr>
<td>Brassica sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorghum bicolor</td>
<td>Sorgoleone</td>
<td>Phalaris minor, Coronopus didymus, Cyperus rotundus, Solanum nigrum, Amaranthus retroflexus, Ambrosia artemisiifolia</td>
</tr>
<tr>
<td>Oryza sativa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypnum plumaeform</td>
<td>Momilactone</td>
<td>Echinochloa colonum, Amaranthus lividus, Digitaria sanguinalis, Poa annua</td>
</tr>
<tr>
<td>Artemisia annua</td>
<td>Artemisinin</td>
<td></td>
</tr>
<tr>
<td>Piper sp.</td>
<td>Sarmentine</td>
<td>Leptochloa filiformis, Taraxacum sp., Chenopodium album</td>
</tr>
<tr>
<td>Eucalyptus sp.</td>
<td>essential oil</td>
<td></td>
</tr>
<tr>
<td>Callistemon citrinus</td>
<td>leptospermine</td>
<td></td>
</tr>
<tr>
<td>Leptospermum scoparium</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Soltys et al. (2013)

Cover crops with allelopathic properties prevent weed seed germination. For example, if cash crops are planned to be sown in early spring, winter annual cover crops should be selected. On the other hand, if cash crop is to be sown in late spring or early summer, overwintering crops should be used. Annual cover crops can be used as mulch, or can be destroyed or left to die (Anonymous, 2022). Datura stramonium increases the production of allelochemicals under the conditions of decreased humidity (Dias & Dias, 2000). The process of using plants with allelopathic properties is called biofumigation. It is performed by growing plants of the mustard genus (Brassica juncea and B. napus) until anthesis, after which they are mulched and incorporated by tillage. Consequently, isothiocyanates are released to prevent weed germination and reduce phytopathogenic fungi (Mattner et al., 2008).

Organic herbicides

Acetic acid (concentrated vinegar), essential oils and non-synthetic herbicidal soaps are natural materials used for weed suppression. Quite a few of herbicide products contain acetic acid and vinegar. The essential oils of clove, citrus, cinnamon, lemongrass oil, etc. are active ingredients of a number of plant-based and natural herbicides. Herbicidal soaps such as ammonium nonanoate and pelargonic acid are non-selective synthetic herbicides used in weed control and suppression. Table 4 shows the examples of organic herbicides based on naturally derived active ingredients. The majority of these herbicides usually destroy any tissue of weed plants they come in contact with, including both broadleaf and grassy weed species (Tiwari & Kanissery, 2021).

Table 4. Examples of organic herbicides

<table>
<thead>
<tr>
<th>Active ingredients</th>
<th>Example Product(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid (vinegar)</td>
<td>Vinagreen (Weed Pharm, Fleishman’s Vinegar)</td>
</tr>
<tr>
<td>Acetic acid + citric acid</td>
<td>AllDown (SummerSet Products)</td>
</tr>
<tr>
<td>Citrus oil (d-limonene)</td>
<td>Avenger Weed Killer (Avenger Products, LLC)</td>
</tr>
<tr>
<td>Clove oil (eugenol)</td>
<td>Weed Slayer (Agro Research International)</td>
</tr>
</tbody>
</table>
Clove oil + cinnamon oil  Weed Zap (JH BIOTECH, INC.)
Clove leaf oil  Matran EC (EcoSmart Technologies, Inc., Franklin, Tenn.)
Lemongrass oil  GreenMatch EX (Marrone Bio Innovations)
40% Ammonium nonanoate  AXXE (BioSafe Systems)
Pelargonic acid  Scythe (Dow AgroScience)
Citrus oil (D-limonene) (55%)  AG optima (AVENGER Products)
Pelargonic acid (33 g/L)  Bio Unkrautfrei AF (Solabiol)
Clove and thyme oil (2%)  Bioganic Broadleaf Killer
Clove oil (12%)  Burnout (BONIDE Products LLC)
Eugenol (5.0%)  EcoSMART® (EcoSMART Technologies)
Citrus oil (D-limonene) (70%)  Fast acting weed killer Concentrate (AVENGER Products)
Pelargonic acid (86 g/L), maleic acid hydrazide (30 g/L)  Finalsan AF Unkrautfrei Plus (NEUDORFF)
*Cymbopogon citratus (50%)  GreenMatch Ex (Marrone Bio Innovations)
Pelargonic acid (237.59 g/L)  Herbistop (COMPO)
Clove oil (50%)  Matran EC (EcoSMART Technologies)
Pelargonic acid (10%), pine oil (Pinus sylvestris)  Organic Interceptor TM (Marrone Bio, Innovations)
Clove oil (8%)  Phydyura™ (Soil Technologies Corp)
Pelargonic acid (699.4 g/L)  RapidGo (PROGEMA GmbH)
Pelargonic acid (57%), C6-C12 fatty acids (3%)  Scythe Herbicide (Mycogen Corporation)
Clove oil (45%), cinnamon oil (45%)  Weed Zap® (JH Biotech Inc)

*Source: Tiwari & Kanissery (2021); Acheuk et al. (2022)

Pre-emergence organic herbicides

Maize gluten meal (MGM). Maize gluten meal (MGM) is an organic herbicide, initially acknowledged as a pre-emergent treatment, which could be used to inhibit seed germination of grassy annual weed species (Christians, 1991). This is the by-product of the wet-milling process of maize. The protein fraction of maize gluten meal consists of approximately 60% protein and 10% nitrogen. It has been used as dog, fish, and livestock feed. Maize gluten meal is made and can be acquired in the form of powder, pellets, or granules (Webber et al., 2012). In the Biopesticide Registration Act, the US Environmental Protection Agency waived all the required toxicology data for MGM under the following circumstances: the product is naturally occurring, the product possesses a non-toxic mode of action, corn gluten meal is considered GRAS (Generally Recognized As Safe) and can be used without limitations other than current Good Manufacturing Practices, corn gluten is exempted from the requirements of a tolerance on food when used as a herbicide (under 40 CFR §180.1164), and corn gluten meal is exempted from the requirement of a tolerance when used as an attractant on crops (under 40 CFR §180.1001(d)) (Reilly et al. 2003). McDade & Christians (2000) set up field trials with three sowing dates (July 3, August 20, and June 8 1998). According to their results, MGM applied in amounts of 100, 200, 300, and 400 g·m⁻² to the top 5-8 cm soil decreased the coverage of weeds by 50%, 74%, 84%, and 82%, respectively. Webber et al. (2007a) report that the application of 400 g MGM m⁻² to onions transplanted in the spring resulted in a moderately good (72.1%) total weed control and a good control (82.7%) of broadleaf weeds during the first 46 days after planting (DAP). Furthermore, the yields were not decreased by crop damages (Webber et al., 2007b). According to the glasshouse studies performed by Liu & Christians (1997), the following species were the most susceptible: Medicago lupulina, Plantago lanceolata, Agrostis palustris, Portulaca oleracea, and Amaranthus retroflexus. At the application rate of 1 g dm⁻², root length, plant survival and shoot length were reduced by 70%, 60% and 52%, respectively. At the same application rate, the reduction in root length and plant survival in Chenopodium album, Rumex crispus, Taraxacum officinale, Setaria faberi, Digitaria sanguinalis, Setaria lutescens was more than 50%. Poa annua, Echinocloa crus-galli, Setaria viridis, Dactylis glomerata, Lolium perenne, Agropyron repens, and Abutilon theophrasti were mainly susceptible at 2 g dm⁻².

Mustard seed meal (MSM). White mustard oil is used for biodiesel production, cooking and other culinary uses. Mustard seed meal (MSM) is a co-product of the commercial oil pressing process (Brown, 2006). The seeds are crushed and oil is produced, while MSM is made as one of the by-products of this process. Although MSM can be used as a natural herbicide, it is not selective, and therefore it does not make difference between harmful and beneficial plants. That is why, attention should be paid to the control of weeds not of cultivated plants. MSM is toxic
to the plants and as the organic herbicide can be applied prior to emergence and sowing or planting. It is used to control germination and emergence of weed seedlings. It contains glucosinolates that typically undergo enzymatic hydrolysis to form isothiocyanates, SCN2, nitriles, and other compounds when added to moist soils (Vaughn & Berhow, 2005). Regrettably, it can destroy directly sown vegetables (Webber et al., 2017). In numerous studies, MSM has been used to suppress weeds in sods (Earlywine et al., 2010), onions (Boydston et al., 2011), garden plants (Boydston et al., 2008), potatoes (Boydston et al., 2008), and peppermint (Boydston et al., 2008), etc. The scope of weeds suppressed or controlled by MSM is very broad, including the following species: amaranth (Amaranthus retroflexus L.), green bristle-grass (Setaria viridis (L.) Beauv.), Mexican fireweed (Kochia scoparia (L.) Schrad.), Russian thistle (Salsola tragus L.), lamb's quarter (Chenopodium album L.), barnyard grass (Echinochloa crus-galli L. Beauv.), common sow thistle (Sonchus oleraceus L.), English plantain (Plantago lanceolata L.), common chickweed (Stellaria media (L.) Vill.), hairy crab grass (Digitaria sanguinalis L. Scop.), Italian ryegrass (Lolium perenne L. spp. multiflorum Lam. Husnot), prickly lettuce (Lactuca serriola L.), and wild oat (Avena fatua L.) (Boydston et al., 2011; Handiseni et al., 2011; Yu & Morishita, 2011). According to Hoagland et al. (2008), the phytotoxicity and consistency of MSM made from white mustard were good or higher than that of MSM made from annual rape and brown mustard. The field studies performed by Webber et al. (2017) confirmed the phytotoxic effect of MSM on the autochthonous weeds and seedling establishment of cantaloupe (Cucumis melo L.) var. ‘PMR-45’, cucumber (Cucumis sativus L.) var. ‘Marketmore 76’, yellow squash (Cucurbita pepo L.) var. ‘Crookneck’, and watermelon (Citrus lanatus L.) var. ‘Dixie’. Their results indicate that, although MSM applications provided satisfactory control of broadleaf, grassy, and total weeds, the application of MSM at 2.25 and 4.5 mt/ha1 significantly decreased the crop establishment of directly sown gourd-family plants.

Post-emergence, post-directed, and burndown organic herbicides

Organic post-emergence, post-directed and burndown herbicides are contact herbicides that have to be used before crop emergence or transplantation. They are directed away from established crops to avoid crop damage. These bioherbicides harm the plant cuticle and cell walls, causing dehydration and fast wilting. With these bioherbicides, it is easier to suppress broadleaf, smaller and annual weeds than grassy, larger and perennial weeds (Webber et al., 2012).

Ammonium nonanoate. Ammonium nonanoate is a fatty acid soap salt of nonanoic acid. It is a non-selective contact bioherbicide. In their study, Webber et al. (2011) pointed out that the application of ammonium nonanoate produced better control of the following broadleaf weeds: tumble pigweed (Amaranthus albus L.), spiny pigweed (A. spinosus L.), Mollugo verticillata L., Eleusine indica L. Gaertn., and smooth crabgrass (Digitaria ischaemum (Schreb. ex Schweig Schreb.]). The best weed control for both amaranth species occurred at a rate of 10.8 kg·ha−1 applied at 654 L·ha−1. Ammonium nonanoate was very toxic to Indian chickweed. The lowest application rate and volume provided a weed control rate of 66%, whereas the majority application rates and volumes produced at least a weed control rate of 88%. The control rates of grassy weeds varied from 31–54% to 24–54% in crowfoot grass and small crabgrass, respectively. In the majority of grassy weeds or larger (5 cm) broadleaf weeds, repeated applications might be needed to obtain satisfactory control.

Vinegar (acetic acid). Vinegar (5, 10, 15, and 20% acetic acid) is a non-selective, non-synthetic, contact bioherbicide with no residual activity. Although it kills upon contact, it cannot provide systemic control of weeds (i.e. cannot be absorbed by roots). Vinegar is more effective in suppressing broadleaf weeds than grassy weeds, and less effective in perennial than in annual weed species (Webber & Shrefler, 2007, 2008a, 2008b, 2009b; Webber et al., 2009). The higher acetic acid content and application volume are (e.g., 187 L·ha−1, 374 L·ha−1, 748 L·ha−1, and 935 L·ha−1), the better the weed control is (Webber et al., 2012). Garcia & Youngblood (2017) applied 5, 10 and 20% solutions of acetic acid to young (less than 10 days) and short (up to 4 cm tall) plants. It was hypothesised that if applied very early, lower concentrations of agricultural vinegar (5%, 10%, or 15%) could slow or stop the growth of weeds, allowing for the desired crop to prevail. Their results indicate that when Palmer amaranth (Amaranthus palmeri) is detected early enough, within the first 30 days, the treatment can be performed with applications of 10% or 20% acetic acid despite its glyphosate resistance. This helps the environment because it reduces the accumulation of acetic acid in the soil. Weed control may be successful if acetic acid is applied during hot sunny days (Anonymous, 2022). Depending on the weed size and species, i.e. whether weeds are annuals or perennials, it might be necessary to apply acetic acid more than once for satisfactory weed control.
Clove oil. Clove oil is another post-emergence, non-selective, contact bioherbicide. It is applied in the control of vigorously growing emerged annual and perennial grassy and broadleaf weeds. The higher application rate and the smaller weed size are, the effectiveness of this contact, non-translocated bioherbicide is more significant. Weed control will be better if some organically permitted adjuvants (e.g. extracts of garlic and yucca) are added to the oil. The effectiveness of clove oil in weed suppression may be as strong, or even stronger, as that of acetic acid herbicides. Furthermore, even if smaller amounts of this oil are used, this bioherbicide will still be effective. Weed control with clove oil depends on the plant size, spray volume, and clove oil concentration (Boyd & Brennan, 2006). Evans & Bellinder (2009) observed the potential use of vinegar and clove oil bioherbicide in field experiments with sweet maize, onion, and potato. The effectiveness of the product depended on the weed species and their size at the time of the herbicide use. Broadcast applications of vinegar and clove oil have been found very effective in young, actively growing sweet maize, onion, and potato. Similar to other contact bioherbicides, the suppression of grassy weeds is more difficult than broadleaf ones if weeds are of a similar size (Webber & Shrefler, 2009a).

D-limonene. D-limonene (55%) is yet another post-emergence and non-selective contact bioherbicide used in the control of actively growing emerged annual and perennial grassy and broadleaf weeds. Gettys et al. (2021) estimated the efficacy, selectivity and costs of the following "natural" products: acetic acid and d-limonene (alone and in combination with each other and citric acid) on the invasive floating plants such as water hyacinth (Eichhornia crassipes) and water lettuce (Pistia stratiotes), and broadleaf sagittaria (Sagittaria latifolia) and pickerelweed (Pontederia cordata). These products, coupled with an industry-standard, non-selective, quick-acting, synthetic herbicide (diquat dibromide), were applied once as a foliar treatment to healthy plants. Following the treatment, the plants were grown for eight weeks for the purpose of developing phytotoxicity symptoms. Used at a concentration of 0.22%, Diquat dibromide eradicated all the vegetation treated. Nevertheless, not a single "natural" product alone ensured acceptable suppression (> 80%) of floating weeds, even when applied at maximum concentrations (20% acetic acid, 30% d-limonene). Although citric acid (5% or 10%) did not affect the action of acetic acid or d-limonene, they suppressed floating weeds effectively when used in combination, without causing intolerable damages to indigenous plants. Shrestha et al. (2012) established that d-limonene provided up to 95% weed control one to five weeks after the treatment. Weeds occurring in organic almond orchards can be successfully controlled by monthly applications of steam, flame or d-limonene. Shrefler et al. (2011) used d-limonene as the post-directed control of weeds in organic cantaloupe, whereas Lanini et al. (2010) carried out studies in the glasshouse and the field applying d-limonene. On balance, D-limonene is more efficient in younger smaller weeds than larger older weeds, and broadleaf weeds are better controlled than grassy weeds.

CONCLUSION

Compared to conventional agriculture, suppressing weeds in organic farming is a challenging task because the application of herbicides is not allowed. Accordingly, a more comprehensive and in-depth understanding of the biology of weeds and crops (and their interactions) is required. In addition to direct eradication, weed prevention methods are the basis of weed control. Breeding plants for weed suppression has long been overlooked because herbicides provide a more efficient and effective method of weed control. More studies are needed to anticipate when a crop grower should take action to suppress and control weeds to accomplish optimum benefits. Suppressing weeds with the methods allowed in organic agriculture (given that the use of synthetic herbicides is not acceptable) results in less expensive production and improved environmental protection. Organic weed control relies on preventive and direct weed control methods, while preserving the health of crops, the soil and the environment.

Acknowledgements: This article is a result of studies performed within the Agreement on the Implementation and Financing of Scientific Research signed between the Ministry of Science, Technological Development and Innovation of the Republic of Serbia and the Faculty of Agriculture in Belgrade in 2023 (Agreement registration number: 451-03-47/2023-01/200116).

Conflict of interest: The authors declare that they have no conflict of interest.

REFERENCES


