Review of non-chemical weed management for green agriculture

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Abstract: This paper reviewed the background and situation for studying and developing non-chemical weed management. Environmental pressure and commissariat safety problems indicate that it is essential to deeply study and develop non-chemical weed management technologies. The paper summarized the pros and cons of the non-chemical weed management technologies in aspects of weed control by agronomic method, mechanical method, thermal treatment method, and biological treatment, discussed the defects of the existing non-chemical weeding methods, and put forward some suggestions: (1) The description on the experiments and operation of the non-chemical weeding technologies is suggested to be standardized in order to compare the performance of different weeding methods. Some important information on name of equipment, consumption capacity, working width, travel speed, and weed control levels should always be included in the experimental descriptions; (2) An integration of combinations or sequences of various weed control techniques is suggested to be used to reduce the risk of a selective pressure leading to the predominance of certain species; and (3) It is also suggested for further improvement of the existing weed control methods and further development of the weed detection technology originally developed for precision chemical application in order to use them in non-chemical weed management.

Keywords: weed control, management, non-chemical technology, mechanical weed control, biological weed control

DOI: 10.3965/j.issn.1934-6344.2010.04.052-060

Citation: Deng Wei, Chen Liping, Meng Zhijun, Wu Guangwei, Zhang Ruirui. Review of non-chemical weed management for green agriculture. Int J Agric & Biol Eng, 2010; 3(4): 52－60.

1 Introduction

Weeds can be seen everywhere during the growth of the crop, it fiercely battles with crops for water and nutrients, strongly disturbing the normal growth of the crop and resulting in severe yield loss and quality reduction. More than 1,400 plant species are considered as weeds in China, 364 species are commonly found in agricultural fields and 37 are listed as malignant weeds[1]. In China, weed jeopardizes nearly 40 million hectares of farmland annually, causing a 4-billion-kg and 2.5-billion-kg loss to wheat and corn, respectively[2]. In order to reduce the losses, weed should be eradicated in the crop's growth period especially in their seedling period. According to the statistics of Agricultural Technology Extension Center of the Ministry of Agriculture, the amount of herbicide used in 2009 was nearly 97,800 tons, accounting for 30% of the total consumption of farm chemical[3]. The time we spend in weeding is as much as 2–3 billion working days, accounting for 1/3–1/2 of the total agricultural employment[4]. In order to maintain yields of crops, weeds must be controlled. Many weed control methods are currently available, but application of chemicals is the major way due to its high efficiency.

However, chemical weeding usually takes the way of widespread spraying, which can not only waste herbicides but also cause ecological environmental hazards and

Received date: 2010-04-06 **Accepted date:** 2010-11-25

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agricultural pollution[5]. Widespread use of chemical weeding methods has caused many serious problems, such as environmental pollution[6,7], commissariat safety[8,9], decrease of biological diversity[10], changes in the weed community[11,12], resistance of weeds to herbicides[13,14], and soil acidification[15,16]. Regulation 2092/91 issued by European Union (EU) in 1991 and the Standards set by UK Organic Food Standard Registration Agency in 1999 both clearly stated that chemical weed control methods are strictly prohibited in organic agriculture[17]. Furthermore, The Food Quality Protection Act (FQ-PA) established by the US government in 1996 also set strict regulations on the maximum level of pesticide residues in food product[18]. In China, food safety is a great public concern, including pesticide residue on agriculture produce. Considering that herbicide is accounting for a significant portion of all pesticides applied in China, non-chemical weed management will help to address this issue as well as reducing environmental pollutions resulted from herbicide usage.

Problems with herbicides, including underground and surface water contamination, and pesticide residues in food, have sparked public awareness and restrictions of herbicide use. These problems have challenged weed scientists to consider alternatives and integrated systems of weed management to reduce herbicide inputs and impacts. Moreover, herbicides are an exhaustible resource, so new approaches to merging soil conservation and non-chemical weed management are needed. Non-chemical weed management is defined as the control of weeds in the field without using chemical products. Some positive aspects of non-chemical weed control are: the reduction of environmental impact, the maintenance of low but stable weed population, improvement of soil nutrients and water quality. Several non-chemical weed control methods and technologies are discussed below.

2 Non-chemical weed control technologies

2.1 Weed management by agronomic method

Plowing: The role of tillage for weed control is to bury the weeds and its seeds deep in the ground so as to make it difficult to germinate. However, this is just a short-term control method. In a long run, this method will bring more trouble to weed control because the buried seeds which will be plowed out during the next turn of tillage would maintain more vigorous germinating capacity. Nowadays, minimal-tillage or no-tillage is promoted in most farming areas for soil conservation. However, grassy weeds and perennial weeds have increased in no-tillage fields[19].

Rotation cropping and alternate husbandry: Rotation cropping produces a kind of unstable soil environment and destructs the weed growing environment to prevent the weeds from forming dominant species. The key of rotation is to choose types of rotation crops and reasonably arrange cultivating sequences. According to foreign experiences, rotation cropping between rice and soybean, or peanut, or cotton, or wheat, or other crop, can prevent the hazard of enemy weeds, such as *Sagittaria* and barnyard grass (*Echinochloa crus-galli*). Moreover, rotation cropping between cereal crops and dicotyledonous crops can decrease the population density of incidental weeds[20]. However, at present, the majority of scientific research about the effects of rotation cropping on weed suppression does not consider their economic and market factors.

Breeding of new crop varieties: Crop varieties with rapid crop growth, vigorous seedling growth, and larger leaf area can inhibit the growth of weeds. Therefore, we can access to excellent crop varieties which own properties of inhibiting weeds species through selecting breeding techniques, such as gene technology. Grundy and others' studies showed that the traditional varieties of high-straw winter wheat expressed stronger inhibition to weeds, compared with the modern short-straw varieties[21]. Allelopathy, the chemical interference between plants, is receiving increasing interest as different systems of integrated weed management for organic and low-input agricultural systems development[22-24]. It is becoming apparent that allelopathy plays a significant role in the competitive ability of cereals against weeds; barley, wheat and rice cultivars with high allelopathic activity have been identified[25].

Other agronomic weed control methods: Rational close planting, intercropping, and narrow-row sowing can also help with weed suppression[26]. Seed coating

technology contributes to formation of sound seedlings and improvement of germination rate. The cultivation measures which make crop sprout earlier, stronger, and more uniform can make the crop establish competitive advantage which aids in suppressing weed growth[27]. Mulching weeding method can be used to suppress sprouting and emergence of annual weeds, and reduce soil erosion in organic farming systems, but ineffective for deep-rooted perennial weeds[28,29]. Hanada reported that mulching with appropriate materials has a number of effects: it increases the soil temperature, conserves soil moisture, texture and fertility; and controls weeds, pests and diseases[30]. The effects of plastic mulch on weed control were reported in the literature[31]. They reported that the absence of light with black plastic mulch didn't allow photosynthesis under the film and therefore weed growth was depressed. On the contrary with transparent film, the presence of light with the improved condition for growth (heat, moisture, good soil structure, etc.) encouraged weed growth. Ligneau and Watt's[32] study suggested that the coverage of 3 cm-thickness-mulch can suppress annual weeds emergence. The materials used to cover can be plants (such as straw, bark and urban green garbage), and synthetic materials[32,33]. Soil temperature and soil moisture were highest under polyethylene[34]. It was indicated that the type of ground cover significantly affected temperature in the upper 12 cm of the soil. The highest soil temperatures were observed under black plastic mulch followed by bare ground. The high soil temperatures associated with certain ground covers may have reduced entomopathogen detection or survival.

2.2 Mechanical weed control

Hand weeding: The disadvantages of this method are labor-intensive, difficult, time-consuming, and inefficient. However, its advantages are no requirement for initial equipment investment, and easy to be used in local areas and small field plots. Hand hoeing is still the main weeding method utilized in many developing countries, such as Nigeria, Afghanistan, Turkey, and the mid-west area in China because of the readily available and relatively low-cost labors[35].

Brush weeding: This method can be used to pull out and bury the weeds between crop lines and inner-rows. However, the operation needs to be conducted in wet weather to achieve high weed control efficiency and decrease the dust caused by rotating brush. The most common types of brushes used are the vertically rotating cylinder brush and the horizontally rotating disc-brush type. The bristles are usually made of polypropylene or steel. The cons of this method are high vibration levels and excessive noise levels during brushing which can occur and pose unacceptable working environments for the operator, especially for hand-pushed machines[36].

Harrow weeding: This method is widely used in non-chemical weed control at pre- and post-emergence stage of weed seedlings. Its cost is relatively low. Harrowing practice can contribute to competitive advantage of crop seedlings and level the ground in order to facilitate the follow-up weeding treatment. However, Turner considered that harrowing is not necessary if there are few weeds after sowing, because harrowing not only has no effects on weed control, but also may cause damage to crop[37].

In addition, other mechanical equipment, such as mechanical hoe, shallow-breaking shovel, mowing machine, and so on, can be used to control weeds in fields. However, all mechanical weed control methods will result in serious damage to soil structure, causing severe loss in soil structure and soil erosion by wind. Thus, mechanical weed control methods should be used cautiously in places where water resources are scarce. While conservation tillage has been widely used, the problems of weed control still exist. In order to reduce environmental pollution and improve the quality and safety of agricultural products, some emphasis should be placed on the study of non-chemical weed control technologies and methods so as to adapt them to the developing trend of green agriculture.

2.3 Thermal weed control

Thermal weed control is defined as rapid heating of plant tissues to destruct plant cell integrity[38]. The effect of thermal weed control largely depends on the efficiency of heat conduction into plants as well as weed growth stage. The leaves of sprouts can be heated up to 70℃, while as the fleshy and hirsute leaf blades and

reptile weeds need longer heating time[39]. Thermal weed control methods include flaming[40], hot water[41], hot foam[42], steaming[43], hot air[44], electrocution[45], infrared radiation[46], microwave[47], and so on. All thermal weed control methods can be classified into two categories: (a) direct heating (flaming, infrared radiation, hot water, hot air, hot foam, etc.); (b) indirect heating (electrocution, microwave, laser radiation, ultraviolet radiation, etc.)[44].

Flame weeding: This method heats up weeds to about 60℃ to 70℃ with a propane flame by using specialized equipment. The heating leads to expansion of the cell sap, burst of the cell wall, and coagulation of the protein in weeds, which then make the weeds withered. It was stated in the literature[48] that the protein in leaves was completely damaged when the leaves were heated to 70℃, and all the cell structures were destroyed when the temperature was raised to 100℃. All types of weed seedlings could be killed directly in the effect, and even the mature weed plants could be removed through repeated application. LPG- fuelled (Liquefied Petroleum Gas) flame weeders have now been established as a part of the organic grower's machinery complement. The aim of a flame weeding operation is not to burn off the weeds but to apply sufficient heat to severely damage the plant cells so the plant will eventually wither and die. The technique involves raising the plant tissue to a temperature of 100℃ from base temperature, in order to burst the cell membranes. Coagulation of proteins occurs between 50℃ and 70℃. The accurate measurement of temperatures of small plants for short time periods is not easy because it involves many factors. Sprouting leaves can be heated to 70℃ in one-tenth, while the fleshy and hairy leaves and creeping weeds need longer time[49]. Burning propane does not produce any toxic residues and does not pollute the environment. The main drawback is fire hazard[35]. The cost of this method is relatively lower than hand weeding, but the initial investment is much higher. Hence, it is suggested that a long and low shield should be added in design of flaming weeder so as to guarantee combusting gases as close to the ground as possible[50]. The angle between the burner and the ground should be within the range of $22.5^{o}-45^{o}$ [51]. However, the method is seriously affected by the weather.

Hot water weeding: In the USA, hot water equipment for weed control, called Aqua Heat, was introduced in the early 1990s[52]. Preliminary studies showed that the hot water method was comparable to glyphosate treatments for controlling most annual and young perennial weeds. However, repeated treatments are needed to control older perennial weeds[53]. Weed age also largely influences total energy input; the energy consumption at six-leaf stage is three times of that at two-leaf stage[54]. The disadvantages of this approach included restriction of operating in raining days and demanding large amount of water which makes equipment bulky. When the boiling water is applied in the soil, the heat loses very quickly and the efficiency of heat conduction is very low because of its little contacting area and short contacting time with leaf blades. Furthermore, hot water is too difficult to control because of its high flowability[41].

Steam weeding: The mixture of vaporized water and steam is sprayed toward the weeds accurately by using sprinklers in this method. One time of treatment can eliminate most of annual weeds and early perennial weeds, and two treatments can eliminate matured perennial weeds. Although this method has a less effect on roots, repeated treatments can remove the part of the weeds above the ground which leads to no nutrition supplied to the roots and makes the weeds die. Compared with hot water, steam has a considerably higher heat transmission coefficient which ensures more heat transferred to plants during contacting. However, steam is easier to volatilize than liquid water so that heat is easy to lose. The cons of the method are its initial investment for steam equipment is extremely high and the operation is affected seriously by environment and weather[42].

Hot air weeding: Studies showed that the thermal efficiency of dry hot air was lower than for hot air with steam. The working speed and efficiency of hot air weeding became higher when the content of steam in hot air was increased so that the consumption and cost were reduced[43].

Electrocution weeding: Electrocution weeding is classified into two categories, which are spark discharge and electrical contact. Both of them need voltage around 20 kV to be effective for weeding. For the first case, a pair of electrodes is put on each side of the plant, or letting one electrode suspended above the plant. The second case makes a high-voltage electrode touching the weeds. Damage severity of the weed relies on the level of voltage and the contact time, as well as the plant species, morphology and age, and furthermore, the amount of wood fibers contained in the weeds[44]. Diprose and Benson reported some damage to roots and rhizomes of weeds after the current flew through a substantial part of the tissue and left the root system especially when the soil was dry[55]. The prominent disadvantage of electrocution weeding is the high voltage which would hurt the operators and passers-by, especially in urban areas.

Infrared radiation weeding: The gas burner heating the surface of ceramic or metal emits heat radiation to the target plant. The intense heat lets the water in plant cells boil, leading to cell rupture. Compared with flame weeding, this method can be used even in the place with high fire hazards. However, infrared radiation will severely be interfered by the shadow of the light[46].

Microwave weeding: Sartorato and his co-workers' study revealed that microwave weeding method might not be suitable for weed control in fields although microwave irradiation could effectively control different kinds of weed species. Because it needs such high energy consumption and high microwave power to satisfy weed control which are hazardous to people and its energy loss is remarkably serious[47].

Laser radiation weeding: Laser devices concentrate a large amount of energy into a narrow laser beam and quickly and accurately focus the laser beam on the targets. The energy in per unit area is high because the laser beam can be focalized on a tiny area (point). Studies reported that CO_2 laser could be used as a physical cutting method of weed control. This method can also reach the purpose of weed control without cutting down the weed stems[56]. A three-year experimental research has ever been done in the US to demonstrate the possibility of control of water hyacinth by using of laser radiation. The results showed that the laser radiation just could slow down the weed growth but it could not completely eradicate the weeds[57].

Electrocution, microwaves, laser radiation, and so on, have all been studied to try to be used as weed control methods. However, they all have not been in practical application because of its high energy consumption, low efficiency and insecurity for operators.

Hot foam: Hot foam can keep in contact with the weeds for a longer time and on a larger surface so that heat exchange time and area are increased due to its anti-sag property, which is also beneficial for controlling of high-stalked weeds. The film of foams can prevent the heat from rapidly releasing with the hot water flowing. The feature serves as an effect of temperature insulation layer, which ensures the temperature around the weeds is relatively stable. Therefore, hot foam weed control method has the advantage of less susceptibleness to the weather changes, security, high application accuracy, high speed, and low cost. The results of Kempenaar's experiment showed that the additional foam layer could improve the efficiency of thermal weed control, and speeding up the travel speed had no negative effects[58]. Bridge sprayed biodegradable foam on weeds once a month using Waipuna ^{TM} hot foam weeder in Sep., Oct., and Nov. in 2003. The foam dissipated in a few minutes. The treatment effect was observed after a few hours. The results showed that the killing rate of weeding by using the hot foam was same as that of glyphosate, both are 50%[59].

The foam can be derived from the mixture of coconut sugar and corn sugar[38,60]. As hot foam weeding is a non-toxic method and valid for various weeds. Therefore, this technology has some practical value and importance in the emerging market for organic agriculture and pollution-free agricultural production. The technology also can be used as a weed control method in public areas, such as schools, municipal streets, roads and railway and other hard surfaces, so as to reduce the possibility for the contamination of urban drinking water and air. Thermal foam technology can also be used to kill and control of mould, bacteria and pests in soils.

Hot foam weed control does not damage the soil surface and can be matched with minimum cultivation. Furthermore, some thermal weed control methods are not bound by the windy and rainy weather, easy to operate, safe, faster than hand-weeding, and low-cost[38]. To a certain degree, it has some application prospects in green agriculture and organic weed managements.

2.4 Weed biological control

Weed biological control is a kind of method which controls the weed floras affecting the human economic activities at a tolerable level in economy, ecology, and landscaping aspects, by taking prudent use of the specificity of host ranges for phytophagous animals and plant pathogenic microorganisms[61]. In theory, weed biological control which is primarily based on the principles of biogeography, population ecology, community ecology implements regulation and control on target weeds on the basis of confirming the relations among natural enemies, parasites and environment. Its characteristics are environmentally safe, effective and lasting control, low-cost prevention and treatment, and so on. So it appears to have a strong vitality and has become an independent system of specialized subjects[62]. Biological control methods on weeds include releasing of natural enemies of weeds, using of fungi, and using of allelopathy of phytotoxin[63]. Over 200 kinds of organisms with different bio-control effects have been developed around the world so that nearly 100 species of malignant weeds have been effectively controlled[63].

3 Recommendations for future study

3.1 Problems

1) Compared with chemical weed control, non-chemical weed control is generally considered as less cost-effective. This is mainly because of the fact that non-chemical weed control methods require repeated treatments and sometimes are labor-intensive. For example, in thermal weed control, the travel speed should be low in order to achieve adequate control on weed and reduce the possibility of weed re-growth. To obtain effective control, more frequently repeated treatments are required than chemical weed management, thereby increasing the costs of labor and fuel[44]. Therefore, many researchers have given much attention to improving the performance and efficiency of the most widely used methods and thereby lower the consumption cost.

2) One of the main disadvantages for non-chemical weed control is a lack of proper definition of the efficiency of the weed control methods and a lack of standardized descriptions of the experiments to make it comparable for each weed control method.

3.2 Need for further research

First, different weed control techniques should be integrated together to reduce the risk of a selective pressure leading to the predominance of certain species. Repeated use of any weeding method is apt to cause a shift in the weed flora to resistant or tolerant species. Such shifts would reduce the effectiveness of certain weed control strategy. As a kind of strategy, brushing and harrowing can be used occasionally to clean-up heavily infested areas, but may damage vulnerable soil surface and degrade conditions of soil moisture. Thermal weed control can be applied at regular intervals throughout the season to keep weeds at a reasonable level.

Second, it is necessary for further development and improvement of the existing weed management methods to increase the energy utilization efficiency. Likewise, it deserves further investigations and development of the weed detecting technologies originally developed for precision chemical application, such as spectral discrimination for weed detection in field, and usage of them into non-chemical weed control. However, the cost of sophisticated equipment would need to be balanced against faster operation speed, consumption in water and energy, and reduced labor costs.

Third, it is necessary to study and adjust the energy dose to various weed floras, according to the plants' morphology, flowering period, and environmental conditions. For example, for weed control along the roads, weed control level is often determined by aesthetic considerations and different pavement modes. Therefore, weed control strategies dividing the infested areas into different levels should be considered in order to classify the weed control level according to the required quality, usage and placement. The levels could be

ranged from no weed control at all to a very high level of weed control. The purpose of the strategies is to help the farmers or local administrators to plan weed control schedule and give priority to the urgent areas so that the weed management could go from the present relative short-term operational planning to long-term strategy planning.

Finally, it is suggested that some important information on name of equipment, consumption capacity, working width, travel speed, and the level of weed control should be included in the experimental descriptions.

4 Conclusions

Techniques for non-chemical weed control have been developed to reduce chemical costs in conventional agriculture, in response to environmental pressures and to provide for the needs of organic food production. A wide range of equipment is available to cover the major crops grown. However, further in-depth study still needs to be done urgently because a successful non-chemical weed control technology requires a well-managed, integrated system and more attentions in detail. Future work is required to research the effects of heat from thermal techniques on soil micro organisms, and weed seed germination and viability. The effects of the combinations of different soil/weed/time on the success of the weeding operation and on the soil structure also merit attention.

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