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Bioherbicides: Dead in the water? A review of the existing products for integrated weed management

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ABSTRACT

The intensive use of synthetic herbicides is questioned for many reasons. Bioherbicides, as integrated weed management tools, however, have the potential to offer a number of benefits such as increased target specificity and rapid degradation. Despite the efforts to identify effective bioherbicide agents in laboratory and field, only thirteen bioherbicides are currently available on the market. Since 1980, the number of biopesticides has increased around the world, while the market share of bioherbicides represents less than 10% of all biopesticides. Nevertheless, weed management implemented at the cropping systems scale needs bioherbicides because of legislation to drive weed management away from heavy reliance on chemicals, the global increase in organic agriculture, the need of both organic and conventional agriculture to increase weed control efficiency, concerns about herbicide resistance, and concern from the public about environmental safety of herbicides. Consequently, we review here the existing products on the market and describe their history, mode of action, efficacy and target weeds. This review is unique because we also discuss the role of bioherbicides in integrated weed management: to manage soil weed seedbanks with seed-targeted agents in addition to primary tillage, to increase the efficacy of mechanical weeding because bioherbicides are more effective on seedlings, to increase the suppression effect of crop cultivars by first slowing weed growth, to terminate cover crops particularly in conservation agriculture, and finally to manage herbicide resistant populations.

1. Introduction

Crop losses due to weeds continue to reduce available production of food and cash crops worldwide (Cramer, 1967; Oerke et al., 1994; Oerke, 2006) even if weeds are known to support ecosystem services in farming landscapes (Marshall et al., 2003). Strategies of weed management can vary, but now mainly rely on the use of synthetic herbicides (Thill et al., 1991). The intensive use of synthetic herbicides in the last fifty years has considerably increased productivity, but with striking environmental and ecological impacts (Soule et al., 1990; Stoate et al., 2009), which have been identified for many decades (Wauchope, 1978).

The heavy reliance on synthetic herbicides to control weeds has been questioned for many decades, and is still being questioned, as the issues caused today are even more significant. Of the 15 molecules coming from plant protection products found in streams and rivers in France in 2012, the most frequently found were herbicides or their metabolites (French Ministry of Ecology Sustainable Development and Energy, 2015). Consequently, the French and European legislation has pulled many products or active ingredients from the market (Barzman and Dachbrodt-Saaydeh, 2011; Chauvel et al., 2012). Thus farmers have to manage weeds with even fewer chemical tools that often contain only one active ingredient (or one chemical family) and which favour the occurrence of phenological adaptations (Mortimer, 1997) and resistant genotype selection (Chauvel et al., 2001). The emergence of resistant individuals among weed populations is an increasingly important issue worldwide (Heap, 1997) and weed management strategies must change to face this issue (Colbach et al., 2016).

Weed management faces the same issues as in the two past decades, i.e. yield losses (Oerke, 2006), reliance on synthetic herbicides (Chauvel et al., 2012), herbicide resistance (Chauvel et al.,

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2001), etc. Weed management also faces new challenges, particularly because agriculture worldwide faces increasing economic, environmental and social pressures (Lechenet et al., 2014; Petit et al., 2015). Sustainable weed management is especially important in the context of these pressures because ideal cropping systems could: allow farmers to be economically sustainable, decrease agriculture's environmental impact, and respond to the social pressures from the public about food safety and security.

Sustainable weed management is one of the main challenges for both organic agriculture and conventional agriculture. Future weed management has to consider new tools, in addition to those existing, as a part of integrated weed management. Bioherbicides are currently underused for many reasons (Ash, 2010; Auld and Morin, 1995), although we will not detail them here. Even though research has long been conducted on weed biocontrol, few biocontrol products have actually been launched on the market. Bioherbicides should be reconsidered as a tool for integrated weed management because: (i) legislation will drive a move from chemical weed management to new options; (ii) the extent of organic agriculture is increasing throughout the world and needs new tools to diversify the selection pressure on weeds and increase in weed control efficiency; (iii) both certified organic agriculture and conventional conservation agriculture need tools to manage weeds and reduce their reliance on synthetic herbicides; (iv) herbicide resistance will be one of the biggest challenges in the next decades; (v) finally, public concern about environmental safety of herbicides has increased interest in developing effective nonchemical weed management methods. Consequently, we provide here a short review of the existing bioherbicides on the market and perspectives on the integration of bioherbicides in cropping systems for integrated weed management.

2. Biocontrol

Using biocontrol for pest management consists of applying the natural interactions that drive inter-species relationships to the control of the balance of pest populations, rather than on their eradication (Herth, 2011). Biocontrol products represent an array of tools to be used alone or in association with other plant protection methods (Herth, 2011). We consider biocontrol agents to be categorized into four groups: macro-organisms (e.g. predators, parasitoid insects, nematodes), micro-organisms (e.g. bacteria, fungi, viruses), chemical mediators (e.g. pheromones) and natural substances (originated from plant or animal). Among these four categories, the last three belong to plant protection products, which fall under the 1107/2009/CEE European regulation (Villaverde et al., 2014).

Micro-organisms, macro-organisms, and natural substances are the most investigated biocontrol agents for weed control (Hinz et al., 2014; Zimdahl, 2011). In our review, only micro-organisms and natural substances will be considered. Micro-organisms can be fungi, bacteria or viruses, whereas natural substances are derived from plants, animals or minerals. A review of the scientific literature on the existing products on the market reveal that biocontrol agents targeting weeds are weakly developed compared with biocontrol agents targeting other pests and diseases.

3. Bioherbicides

Bioherbicide products are adapted from natural substances already present in the environment, so they are expected to be more environment-friendly. The half-life of bioherbicides is usually shorter than that of chemicals (Duke et al., 2000). However, that a product is naturally derived does not mean it is actually harmless. Certain natural toxins produced by plants or micro-organisms are present in the environment and can be a danger to animals, including mammals. The activity spectrum of natural toxins should be carefully evaluated (Duke et al., 2000).

3.1. Definition

In 1971 bioherbicides were defined as substances intended to reduce weed populations without degrading the environment (Conseil International de la Langue Française, 1971). Since then their definition has evolved. According to Bailey (2014), bioherbicides are products of natural origin for weed control. Bioherbicide products can be either living organisms, and more specifically micro-organisms, or products derived from living organisms, including the natural metabolites produced by these organisms in the course of their growth and development.

3.2. Modes of action

The mode of action of bioherbicides is similar to plant-pathogen interaction mechanisms and allelopathy (Harding and Raizada, 2015). In the case of plant-pathogen interactions, the biocontrol agent has to circumvent the weed's defense reactions. The relationship between the two individuals has to be compatible for the pathogen (i.e., the biocontrol agent) to be able to infect the target plant (Andanson, 2010). Different virulence factors are directly or indirectly involved in this infection process. Firstly, the agents could be enzymes that degrade plant cell walls (pectinases, cellulases, ligninases, etc.), proteins and lipid membranes (proteases, peptidases, amylases, phospholipases, etc.). They make it easier for the biocontrol agents to get into and/or spread onto the host plant (Ghorbani et al., 2005). Secondly, the agents could be phytotoxic secondary metabolites and peptides that act as toxins that interfere with plant metabolism (Stergiopoulos et al., 2013). The mechanisms behind this metabolism interference have mainly been demonstrated in crops, rather than weeds, because too few studies have been devoted to weed-pathogen interactions including parasitic plants (Vurro et al., 2009). These toxins directly or indirectly modify the expression of one or more genes which then lead to plant death (Vincent et al., 2012; Torres et al., 2016). Toxins interfere with a specific compound in the plant (an enzyme, a receptor, etc.), so if this compound is missing or altered there is no toxic effect (Xie et al., 2013). Therefore toxins and/or their molecular targets are key determinants to characterize a host/pathogen range (Hoagland et al., 2007; Daguerre et al., 2014). In the case of allelopathy, only molecules extracted from plants or micro-organisms are involved. This type of control corresponds to growth inhibition events that occur in certain agriculture fields. Allelopathy is defined as “a negative or positive effect of chemical compounds produced by the secondary metabolism of plants or micro-organisms, and that have an influence on the growth and development of biological and agricultural ecosystems (except mammals)” (de Albuquerque et al., 2011). A well-known example is hydroxamic acid, produced by maize (Collantes et al., 1998).

These different modes of action of microbial and plant origin provide an outstanding diversity of biochemical compounds that make it possible to target a large number of molecular sites in weeds (Duke et al., 2000). Thus the possibilities for bioherbicide use are wide and should be taken advantage of. Depending on the biological origin of the bioherbicide, its efficiency will be influenced by the specificity and virulence of its biocontrol agent, or on the specificity of the natural substance. Moreover, for the bioherbicide to be stored, marketed, handled and applied, it has to be formulated with co-formulants, the compositions of which are not systematically made public, but which ensure that the product will have an effective mode of action. Additional factors that bioherbicide action