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Review

Allelopathic Influence of Aquatic Weeds on Agro-Ecosystems: a Review

Influência Alelopática de Plantas Daninhas Aquáticas em Ecossistemas Agrícolas: Uma Revisão

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ABSTRACT - Aquatic weeds are higher plants found in the aquatic ecosystem and in anaerobic rice fields, where they have no economic benefits. The continuance of aquatic weeds is more widespread than terrestrial weeds because in aquatic ecosystems there is very little fluctuation in the environmental conditions compared with terrestrial ecosystems. Scientists have been working to address the harmful allelopathic effects of aquatic weeds on the aquatic ecosystem, but limited information is available on the allelopathic influence of aquatic weeds on agro-ecosystems through the release of phytotoxic compounds. Phytotoxic chemicals released by different aquatic weeds into irrigation water and/or directly into rice ecosystems might have a significant inhibitory influence on germination, growth and yield field crops, soil properties and nutrients availability, population and community structure, and weed invasion. However, aquatic weeds might also be used as a potential organic alternative to chemical weed-control, due to the higher susceptibility of terrestrial weeds to the phototoxic chemicals released by aquatic weeds. Natural alternatives to chemical weed control are need of time and are crucial for a sustainable weed control. Chemical weed control is challenged, due to recent increases in herbicides resistance from weeds and to the harmful side-effects of herbicides on the environment. This review is focused on the influence of aquatic weeds on agro-ecosystems, with examples of common weeds in aquatic ecosystems and invasive aquatic weeds found in anaerobic rice.

Keywords: allelopathy, aquatic ecosystem, ecosystem interactions, herbicides resistance management, organic weed control, phenolics, weed invasion.

RESUMO - As plantas daninhas aquáticas são plantas superiores encontradas no ecossistema aquático e em plantações de arroz anaeróbio, onde não têm vantagens econômicas. A continuidade das plantas daninhas aquáticas é mais difundida do que a das plantas daninhas terrestres, pois nos ecossistemas aquáticos há flutuação muito baixa nas condições ambientais, em comparação com ecossistemas terrestres. Os cientistas têm trabalhado para abordar os efeitos nocivos alelopáticos dessas plantas nos ecossistemas aquáticos, mas há informações limitadas à disposição sobre a influência alelopática das plantas daninhas no ecossistema agrícola através da liberação de compostos fitotóxicos. Os compostos químicos fitotóxicos liberados por diferentes plantas daninhas aquáticas na água de irrigação e/ou diretamente no ecossistema do arroz podem ter significativa influência inibitória na germinação, no crescimento e rendimento das culturas, nas propriedades do solo e na disponibilidade de nutrientes, na estrutura da população e da comunidade e na invasão de plantas daninhas. No entanto, as plantas daninhas aquáticas podem ser usadas como uma potencial alternativa orgânica ao controle químico das

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plantas infestantes, devido à maior suscetibilidade das plantas daninhas terrestres aos compostos químicos fitotóxicos liberados pelas plantas daninhas aquáticas. Alternativas naturais ao controle químico das infestantes precisam de tempo e são cruciais para um controle sustentável. O controle químico das infestantes é desafiado pelo recente aumento da resistência aos herbicidas nas plantas daninhas e pelos efeitos colaterais nocivos dos herbicidas no ambiente. Esta revisão está focada na influência de plantas daninhas aquáticas em ecossistemas agrícolas, com exemplos de plantas daninhas comuns em ecossistemas aquáticos e plantas daninhas aquáticas invasivas encontradas em arroz anaeróbio.

Palavras-chave: alelopatia, ecossistema aquático, interações de ecossistemas, gestão de resistência a herbicidas, controle orgânico de infestantes, fenólicos, invasão de plantas daninhas.

INTRODUCTION

Aquatic weeds are troublesome, unwanted and harmful higher plants grown in aquatic ecosystem in water and wet soil; some of them have the ability to tolerate periods of desiccation. Their varied adaptability to different amounts of water and the unfeasibility of a very sharp distinction between water and terrestrial ecosystems makes it very difficult to precisely define them. Aquatic weeds spread very rapidly and have reached alarming proportions in aquatic ecosystems; their invasion into agro-ecosystems may lead to huge economic losses and serious challenges to the sustainability of the worldwide crop production (Aloo et al., 2013). Allelopathy in aquatic ecosystems plays an important role in establishing the composition of aquatic life, as it provides competitive advantages to angiosperms, algae and cyanobacteria, due to their more allelopathic potential, when compared to other autotrophs (Gross, 2003). They also influence the competition between different aquatic plants because of their differential allelopathic potential (Abbas et al., 2015). Studies have revealed that allelopathy exists in all types of aquatic ecosystems, including fresh and marine water habitats, and that all autotrophs including corals, cyanobacteria, micro and macro-algae as well as angiosperms including emergent macrophytes, floating leaved macrophytes and submersed macrophytes are able to release different types of phenolics and other allelopathic compounds in the aquatic ecosystem (Inderjit and Dakshini, 1994; Gross, 2003; Jin et al., 2003). However, allelopathic interactions are different in the aquatic ecosystem compared to the terrestrial ecosystem. In the aquatic ecosystem, released allelochemicals need to be highly hydrophilic in nature and must reach the target site at proper concentrations, without a considerable dilution, as organisms in aquatic ecosystems are completely surrounded by water instead of air. Furthermore, aquatic plant submerged leaves have no stomata, they have a very thin cuticle and loosely connected cells when compared to terrestrial plants (Hutchinson, 1975); these characteristics might allow releasing allelochemicals more easily than terrestrial plants. Allelopathic interactions of aquatic organisms in the aquatic ecosystem have been well discussed by other researchers (Szczepanska, 1987; Gopal and Goel, 1993; Inderjit and Dakshini, 1994; Jackson and Armstrong, 1999; Jüttner, 1999; Neori et al., 2000; Gross, 2003). The influence of allelochemicals released by aquatic plants on terrestrial plants have not been considered during the past, because it was supposed that they had no direct ecological relevance (Gross, 2003). To the best of our knowledge, not even a single review or detailed literature is available on the allelopathic influence of aquatic allelochemicals on agro-ecosystems. However, it is important not to ignore it, because aquatic weeds grown in anaerobic puddled rice have direct allelopathic influence on associated rice crops and following crops in cropping systems (Abbas et al., 2014, Abbas et al., 2016). Aquatic weeds also pollute water in aquatic ecosystems through the release of allelochemicals. Polluted water might be further be used for irrigation purposes. In addition, it is also very important to study the influence of allelochemicals released by aquatic plants on organisms belonging to different habitats because they might be well adapted to the allelochemicals of a certain ecosystem compared to the ones of any other ecosystem (Reigosa et al., 1999). This review is focused on the influence of aquatic weeds on agro-ecosystems, with examples of common weeds in aquatic ecosystems and invasive aquatic weeds found in anaerobic rice. In addition, it is focused on problems on aquatic ecosystem caused by aquatic weeds, their allelopathic influence on field crops, soil properties and nutrients availability, weed species composition and weed invasion and their role in in weed control in agro-ecosystems.

HARMFUL EFFECTS OF AQUATIC WEEDS IN AQUATIC ECOSYSTEMS

Aquatic weeds have gained significant attention since the last century, because of fast-growing world populations and changes in food consumption. Problems associated to aquatic weeds for human beings and agricultural productivity has increased. They are considered a great challenge to the sustainability of the aquatic ecosystem because they influence the life of fish and other aquatic organisms, the diversity of aquatic plants and algae, and the net productivity of aquatic ecosystems (Garry et al., 1997; Davis and Hirji, 2003; Zhang et al., 2007). Aquatic weeds are increasing with an alarming situation, due to leaching and runoff of nutrients from agricultural lands, and to increased human and industrial wastes containing nutrients and microbes that are eventually transported to water bodies (Aloo et al., 2013). Bigger populations of aquatic weeds reduce light penetration to deep layers of water, leading to a reduced primary production; they also influence the characteristics of water and the life of aquatic organisms (Garry et al., 1997; Aloo et al., 2013). Moreover, aquatic weeds create disturbance in hydropower plants, in the intake of water from the catchment area and they also block water outlets during its use for irrigation (Cooke et al., 2005). They also interfere with fishing and other practices, including the cleaning of water bodies, irrigation canals and agricultural practices in crop fields. The invasion of aquatic weeds is also very common (Abbas et al., 2015) and faster than the one of terrestrial weeds, since most aquatic weeds are floating in nature and their seeds and vegetative parts of emerged weeds also move with the water flow from one place to another. These invasive weeds always cause increased diseases and pests because they act as hosts for vectors of different diseases, such as malaria (Aloo et al., 2013). In addition to the described problems of aquatic weeds on aquatic ecosystems, their allelopathic influence on field crops, arable weeds, soil properties and nutrient availability, weeds species composition and weeds invasion in agro-ecosystem are important to evaluate.

ALLELOPATHIC EFFECTS OF AQUATIC WEEDS ON FIELD CROPS

Effects of water soluble allelochemicals of aquatic weeds on field crops

Allelochemicals released by weeds into the aquatic ecosystem influence the growth of different crops by polluting irrigation water. Most allelochemicals are hydrophilic in nature, since water extracts of different weeds have imposed a negative impact on crops and development. Aqueous extracts of purple nutsedge (*Cyperus rotundus*), an important weed of anaerobic rice that grows well in standing water conditions, has been found to decrease seed germination and seedling growth of various crop species, including maize, rice, tomato, cucumber, sorghum and onion (Singh, 1968; Meissner et al., 1979; Garima et al., 2005). Jeyasrinivas et al. (2005) used aqueous extracts from different aquatic weeds at varied concentrations (0, 5, 10, 15 and 20%) against pearl millet cv. C03, cow pea cv. C04, sesame cv. C03 and cucumber. They reported that aqueous extracts from aquatic weeds such as *C. rotundus* had suppressive effects on the seed germination and seedling growth of tested crops. Yang (1992) tested the influence of aqueous extracts from two important weeds of anaerobic rice ecosystem *i.e. C. rotundus* and barnyard grass (*Echinochloa crus-galli*) against the germination and early seedling growth of maize (*Zea mays*). The germination and seedling growth of maize seeds treated with aqueous extracts was significantly inhibited when compared to double distilled water treated maize seeds at the same pH. Aqueous extracts of *E. crus-galli* at different concentrations showed strong inhibitory effects against the radical development and coleoptile growth of various agronomic crops (Bhowmik and Doll, 1979). Angiras et al. (1998) used the aqueous extracts of various weeds to assess their effects on chick pea (*Cicer arietinum*). They stated that aqueous weed extracts reduced germination up to 50% and *E. crus-galli* caused more inhibition in terms of germination percentage and seedling growth, compared to other weeds. Xuan et al. (2006) concluded that root exudates of *E. crus-galli* suppressed the growth of rice, lettuce, and monochoria (*Monochoria vaginalis*) during early growth stages.

Aqueous extracts of *E. crus-galli, E. colona, Cyperus iria* and *Ageratum conyzoides* weeds reduced the germination and inhibited the root and shoot elongation of rice seedlings. The inhibitory effect was stronger against root elongation than shoot elongation of rice (Manandhar et al., 2007). *Echinochloa crus-galli* reduced the germination and seedling growth of rice by releasing allelochemicals, e.g., P-hydroxymandelic acid. The reduction in germination and seedling growth depended on allelochemicals concentration (Gu et al., 2008). *Alternanthera philoxeroides* and *A. sessilis* are two important invasive aquatic weeds found in water bodies, ponds, irrigation canals and anaerobic rice fields. Results from experiments conducted by Mehmood et al. (2014) reported that water extracts of *Alternanthera philoxeroides* and *A. sessilis* caused significant reduction in rice germination, shoot and root length, and seedling vigor index. Leaf extracts from *A. philoxeroides* and *A. sessilis* at 5% concentration caused up to 100% and 49% reduction in rice seed germination, respectively. Water extracts (2.5 and 5 w/v %) of five aquatic weeds such as *A. philoxeroides*, *A. sessilis*, *C. stricta*, *P. barbatum* and *E. crus-galli* were tested on rice and wheat. It was evaluated that all tested weeds caused significant germination and seedling growth inhibition in rice and wheat (Abbas et al., 2014, 2015). The allelopathic potential of *Ageratum conyzoides* has been reported; it is one of the important aquatic weeds infesting field crops (Kamboj and Saluja, 2008). Thus, water-soluble phenolics released by aquatic weeds may severely reduce the growth and yield of field crops, by inhibiting germination and seedling growth. Water-soluble phenolics pollute irrigation water and if they reach receiver crop plants without sufficient dilution they can cause crop yield reduction, due to poor crop stand. Crop-associated aquatic weeds in anaerobic rice can also get competitive advantages over other weeds and crop plants, due to the release of soluble phenolics. Therefore, the allelopathic influence of aquatic weeds can create huge challenges to the sustainability of arable crop production in the long run without considerable attention to understanding the action mechanism and release of allelochemicals from aquatic plants.

Allelopathic effects of aquatic weed decomposing residues on field crops

After harvesting crops, farmers commonly remove weeds but they either leave plant material on the field surface or incorporate it into the soil for decomposition. The allelochemicals in these residues might interfere with the growth and development of succeeding crops, and they may perturb the economic crop production. Allelochemicals released form weeds residues remain active and available for plants afterwards; that may affect the germination and seedling growth of future crops by disturbing basic plant processes, such as interrupting cell division (Deka et al., 2011). Zohaib et al. (2016) have described in detail the mechanisms through which allelochemicals hinder the germination and seedling growth of crops. Allelochemicals influence soil chemical characteristics by releasing significant amounts of phytotoxic chemicals during decomposition; that weaken the soil and decrease the crop growth and yield (Batish et al., 2002). Furthermore, in the soil ecosystem, allelochemicals become directly available to plant roots or/ and indirectly influence them by changing soil characteristics and inhibiting soil micro flora, so they affect the growth and germination of subsequent crops (Kobayashi, 2003). Various studies have shown that residues from several terrestrial weed species released allelochemicals into the soil, thus affecting the performance of associated and next-season crop plants (Qasem 2001; Aziz et al., 2008; Altieri et al., 2011). However, rare researches are available to understand the influence of aquatic weeds residues on field crops.

For example, field grown mature plant residues from aquatic weeds (*C. rotundus* and *E. crus-galli*) were incorporated into the soil to study the phytotoxic inhibition on the emergence and seedling growth of maize. It was revealed that residue incorporation caused significant inhibition to maize in terms of emergence rate and seedling growth (Chang et al., 1992). Growth inhibitory effects of *C. rotundus* residues were investigated by using rice seedlings as bioassay material. Residues caused severe seedling growth inhibition in rice. Amended soil with fresh leaves of *Cyperus rotundus* reduced the leaf area, plant height, roots and shoot weight of rice seedlings. The total phenolic content was higher in soils that were infested by *Cyperus rotundus* residues than in the control soil (Quayyum et al., 2000). Inhibitory effects of plant residues from three dominant aquatic weeds of the North-Western Himalayan region were observed on the emergence and seedling growth of three common cereal crops, including rice, wheat and maize. Residues at 5 g and 10 g in 100 g^{-1} soil concentrations were compared with residue-free soil (control sample). Among the tested crops, maize with larger seed size was the least sensitive to various treatments, while wheat and rice having small seeds were comparatively more susceptible. The weed residue in soil had inhibitory effects on the emergence percentage and shoot length of seedlings. The results showed the allelopathic influence of weeds residue on the physiology of crop plants (Katoch et al., 2012). Residues of *A. philoxeroides,* which is considered an important aquatic weed in anaerobic rice, strongly inhibit rice growth and caused yield reduction up to 50% (Liuqing et al., 2007). Inhibitory responses of *A. philoxeroides* have been reported on different field crops including rice, mustard and lettuce (Paria and Mukharjee 1981; Liuqing et al., 2007). Many aquatic weeds released water soluble allelopathic compounds into soil; they suppressed the growth and germination of crop seeds (Batish et al., 2005; Abbas et al., 2014). Controlled studies were conducted by Mehmood et al. (2014) to test the effects of soil incorporated residues at different concentration (1, 2, 3 and 4% concentrations) from plant parts of *A. philoxeroides* and *A. sessilis* on rice germination and seedling growth. It was investigated whether rice germination, seedling growth in terms of root and shoot length and their dry weight, and seedling vigor index were significantly inhibited by residues at 3 and 4% concentrations when compared to control samples (residue-free soil). Allelopathic effects of residues at two concentrations (2 and 4% w/w) of five aquatic weeds, namely *A. philoxeroides*, *A. sessilis*, *C. stricta*, *P. barbatum* and *E. crus-galli,* were investigated on the germination and early growth of wheat and rice. Results showed that a significant reduction in germination and seedling growth of wheat and rice occurred. *A. philoxeroides* and *A. sessilis* caused more inhibition compared to other weeds (Abbas et al., 2014, 2015). These studies revealed that aquatic weed residues could act as an important factor to inhibit the establishment and plant growth of field crops. Therefore, properly removing aquatic weed residues form water bodies and agricultural soil is crucial to ensure an economical and sustainable crop production. Potential allelopathic effects of different aquatic weeds have been given in Table 1.

EFFECTS OF AQUATIC WEEDS ON SOIL PROPERTIES AND NUTRIENT AVAILABILITY

Aquatic weeds not only have direct effects on crops and weed growth but are also supposed to influence the soil properties and availability of nutrients for crop plants. Allelopathic aquatic weeds may cause changes in soil chemical characteristics by releasing allelochemicals into it (Inderjit and Dakshini, 1998). In this study, soil affected by allelopathic weeds was compared with nearby soil having no exposure to allelopathic weeds. The results proved that the release of allelochemicals influenced soil chemical characteristics including soil pH, potassium (K^+), soil electrical conductivity and chloride (Cl^-). Observable changes were possibly due to the release of water soluble phenolics into the soil (Inderjit and Dakshini, 1998). Different aquatic weeds, including *A. philoxeroides*, *A. sessilis, C. stricta*, *P. barbatum* and *E. crus-galli*, explored a strong allelopathic potential due to the release of water soluble phenolics into the soil. When soil infested with the residues of these weeds was compared with non-infested soil, results confirmed that seedling growth was very poor in infested soil; that may be due to the presence of allelochemicals and/or changes in soil nutrient availability. Jabran et al. (2013) described the mechanisms involved in nutrient dynamics changes in soil in relation to allelochemicals. Normally, allelochemicals are considered to have a strong role in the nutrient availability and nutrient cycling in the ecosystem (Appel, 1993). Different types of water soluble phenolics released by aquatic weeds and phenolic acids are proved to influence the availability of nutrients by creating different type of chemical bonds and complexes with available forms of nutrients (Appel, 1993; Kuiters, 1991). Nitrification processes were also influenced by phenolics involved in the inhibition of oxidation of NH_4^+ to NO_3^- through the inhibition of nitrifying bacteria (Rice, 1984). However, rare information is available on this aspect of aquatic weeds, but it is strongly necessary to evaluate the harmful effects of aquatic weeds on crops. In conclusion, it can be assumed that allelochemicals, especially water soluble phenolics released by aquatic weeds, may influence soil productivity in addition to their direct allelopathic effects.

ALLELOPATHIC ROLE OF AQUATIC WEEDS ON WEED INVASION AND DOMINANCE IN NATURAL ECOSYSTEMS

Allelopathy plays a vital role in the ecosystem. It affects the ability of plants to invade and establish themselves in new ecosystems, by suppressing the growth of existing plants in the natural ecosystem. Allelopathy has been considered a form of non-resource interaction between

Table 1 - Allelopathic effects of some important world aquatic weeds on different terrestrial field crops and weeds

Weed	Donor weed		Recipient crop/weed		Reference
	Weed extract/weed residues	Phytotoxin	Crop/weed	Inhibitory effect	
Ageratum conyzoides L. (Billygoat-weed)	Aqueous extract	ND	Rice	Inhibition of germination and seedling growth	Manandhar et al., 2007
	Volatiles	ND	Peanut, redroot amaranth, cucumber and ryegrass	Inhibit growth and development	Kong et al., 2002
	Leaf residues and their extract and amended soil	ND	Wheat	Inhibit radical and coleoptile length and seedling dry weight	Singh et al., 2003
	Soil amended with residues	ND	Rice	Inhibit root and shoot length and biomass accumulation of rice	Batish et al., 2009
	Soils amended with weed residues	ND	Chickpea, mustard	Inhibition of growth and nodulation	Singh et al., 2004
	Extracts and metabolites	ND	Radish, mungbean, ryegrass, tomato	Growth inhibition	Okunade 2002
	Extracts	Benzoic acid, coumalic acid, gallic acid, protocatechuic acid, p-hydroxybenzoic acid, pcoumaric acid and sinapic acid.	Paddy weeds	Inhibition of germination and seedling growth	Hong et al., 2004; Xuan et al., 2004
Alternanthera philoxeroides (Mart.) Griseb. (Alligator weed)	Water extract	ND	Algal	Algal and cyanobacteria growth inhibition	Zhang et al., 2007; Zuo et al., 2011
	Tissue extract	ND	Mustard, rice and ryegrass	Seedling growth inhibition	Yang 1992
	Extract and residues of different plant parts	ND	Rice	Inhibition of germination and seedling growth	Mehmood et al., 2014
	Whole plant extract and residues	4-Hydroxy-3- methoxybenzoic acid, m-Coumaric acid and p-Coumaric acid	Wheat	Germination and seedling growth inhibition	Abbas et al., 2014
	Extract of different plant parts	ND	Lettuce and barnyard grass		Liuqing et al., 2007
Alternanthera sessilis L. (Sessile joyweed)	Extract and residues of different plant parts	Chlorogenic acid, ferulic acid, gallic acid and vanilic acid.	Rice	Inhibition of germination and seedling growth	Mehmood et al., 2014
	Extract of different plant parts	ND	Lettuce and barnyard grass		Liuqing et al., 2007
	Whole plant extract and residues decomposition	Chlorogenic acid, ferulic acid, gallic acid and vanilic acid.	Wheat	Germination and seedling growth inhibition	Abbas et al., 2014
	Aqueous extracts	ND	Mung bean	Germination and growth	Joshi et al., 2015
Conyza stricta L. (Horseweed)	The whole plant extracts and residues	Chlorogenic acid, ferulic acid and m-coumaric Acid	Rice	Inhibition of germination and seedling growth	Abbas et al., 2014
	The whole plant extracts and residues	Chlorogenic acid, ferulic acid and m-coumaric acid	Wheat and rice	Inhibition of germination and seedling growth	Abbas et al., 2015
Cyperus iria L. (Rice flat sedge)	Aqueous extract	ND	Rice	Inhibit seed germination, shoot and root elongation.	Manandhar et al., 2007
	Extracts and debris	ND	Rice	Inhibit growth	Ismail et al., 2011
Cyperus rotundus L. (Purple nut sedge)	Water extract of tubers	ND	Bajra, cowpea, sorghum, maize, black gram, rice, sesame, sunnhemp and ground nut.	Germination and seedling growth	Singh, 1968
	Plant extract	ND	Corn, rice, tomato, cucumber, sorghum and onion	Seedling growth	Meissner et al., 1979
	Aqueous extracts	ND	Maize	Inhibited the seed germination and plumule and radical growth	Hamayun et al., 2005
	Aqueous extracts and leachates of leaves and tubers	ND	Rice	Seedling growth	Quayyum et al., 2000
	Extract	ND	Banana	Growth inhibition	Singh et al., 2009
	root exudates,	ND	tomato and cucumber plants	Reduce root and shoot growth	Alsaadawi and Salih, 2009
	residues incorporated soil	ND	Sorghum, soybean and cowpea	Inhibit seedling growth	…..
	Volatile compounds released from its shoot and tubers	ND	Mungbean	Reduce seedling r=growth	…...
	Extract and residues	Alkaloids, fla-vonoids, tannins, starch, glycosides and furochromones, and many novel sesquiterpenoids	Rice cultivers	Germination and seedling growth	Geethambigai and Prabhakaran, 2014

Cont. ...

Table 1, cont.

Weed	Donor weed		Recipient crop/weed		Reference
	Weed extract/weed residues	Phytotoxin	Crop/weed	Inhibitory effect	
Echinochloa crus-galli (L.) Beavu (Barnyard grass)	Residues and water extract	ND	Rice	Inhibitory of germination and seedling growth	Manandhar et al., 2007; Abbas et al., 2015
	Whole plant water extract and residues	m-coumaric acid, p-coumaric acid and vanilic acid	Rice and wheat	Inhibitory of germination and seedling growth	Abbas et al., 2014
	Extract	ND	Maize	Emergence and seedling growth	Yang, 1992
	Water extract	ND	Chick pea		Angiras et al., 1988
	Methanol extracts	ND	Cress, alfalfa, lettuce and rice	Growth inhibition	Son et al., 2010
	Root exudates	Phenolics, long-chain fatty acids, lactones, diethyl phthalate, acenaphthene, and derivatives of phthalic acids, benzoic acid, and decane. quantities of diethyl phthalate, decanoic acid, myristic acid, stearic acid, 7,8-dihydro-5,6-dehydrokavain,and 7,8-dihydrokavain	Alfalfa, lettuce, rice, monochoria and paddy weeds	Inhibition of germination and seedling growth	Xuan et al., 2006
Echinochloa colona L. (Swanki)	Aqueous extract	ND	Rice	Inhibition of germination and reduced shoot and root length	Manandhar et al., 2007
	Extract	Cinnamic acid, chloro-genic acid, apigenin, syringic acid, ferulic acid and protocatechuic acid	weed species (*Portulaca oleracea*, *Corchorus olitorius*, *Brachiaria reptans*, *Euphorbia heterophylla, Dinebra retroflexa, Hibiscus trionum, Amaranthus graecizans, Amaranthus hybridus, Convolvulus arvensis, Setaria pumila* and *E.colona)*	Germination and seedling growth inhibition	Gomaa and AbdElgawad, 2012
Polygonum barbatum L. (Knot grass)	Whole plant extract and residues	Caffeic acid chlorogenic acid, m-coumaric acid and p-coumaric acid	Rice and wheat	Inhibit germination and seedling growth of rice and wheat	Abbas et al., 2014, 2015
	Methanol extract of the aerial parts	Sitosterone, viscozulenic acid, acetophenone	ND	ND	Mazid et al., 2011

plants that may improve the potential of specific exotic weed species to become dominant invasive weeds in a new ecosystem, by favoring the growth of some less sensitive plants to allelochemicals and inhibiting the germination and growth of sensitive plants in the natural ecosystem (Ridenour and Callaway 2001; Hierro and Callaway, 2003; Lijun et al., 2010). The allelopathic potential of two invasive *Alternantheria* species in the rice ecosystem was compared with three native rice weeds viz. *Conyza stricta*, *Polygonum barbatum* and *E. crus-galli*. Results revealed that *Alternantheria* species showed a significantly higher allelopathic potential than other native weeds (Abbas et al., 2014). The invasion of *A. philoxeroides* in new ecosystems due to its strong allelopathic effects has been reported (Xie et al., 2010; Mehmood et al., 2014). The strong allelopathic potential of two invasive aquatic *Alternanthera* species viz. *A. philoxeroides* and *A. sessilis,* leads to think that water soluble phenolics released from these weeds play a significant role in the successful invasion of these weeds (An et al., 1997; Abbas et al., 2015). Allelopathic plants may involve genetic changes within nearby growing plants. It may suggest that genotypes that are sensitive to allopathic chemicals have been removed from the gene pool, due to the continuous selection pressure of selective allelopathic chemicals, especially phenolic acids released by aquatic weeds (Lawrence et al., 1991; Abbas et al., 2014).

Allelopathy, a non-resource mechanism, should be considered as an important way to alter resource competition among plants. Ecologists should consider that both resource and non-resource mechanisms work simultaneously in an ecosystem; however, their relative importance depends on the type of plant species and ecosystem. The successful invasion of exotic weeds species in a new ecosystem may be due to their specific novel interaction mechanism (allelopathy) with the recipient ecosystem, since the susceptibility of resident plants to allelochemicals released by invasive weed species allow them to dominate existing native plant communities. Studies focusing on comparisons between allelopathic effects of invader weed species on species originating from where the invader species belong versus species from the recipient community may help exploring the generality of this phenomenon. Additional studies are necessary to evaluate the allelopathic effects of common invasive aquatic weeds species on the weeds and crop species most commonly attacked by the invader in the ecosystem. In conclusion, it may suggest that the unique allelopathic potential of invasive aquatic weeds contribute to their success in a new ecosystem.

USE OF THE ALLELOPATHIC POTENTIAL OF AQUATIC WEEDS TO MANAGE WEEDS IN FIELD CROPS

Weeds have been considered the most troublesome abiotic factor causing yield reduction in field crops since the beginning of agriculture. Synthetic herbicides play an important role in weed control. However, they can have detrimental effects on crops, ground water, soil and human health and cannot effectively control herbicide-resistant weeds (Macías et al., 2007). Herbicides can also create hormesis in weeds that received low doses of herbicides (Abbas et al., 2016; Nadeem et al., 2016). Plant-derived chemicals offer great potential for pesticides because they are biodegradable and comparatively safer for the environment (Petroski and Stanley, 2009). The use of allelopathy for weed control had considerable importance in last few decades, due to issues regarding the sustainability of chemical weed control methods. Water extracts of different allelopathic crops and weeds have been successfully practiced under field conditions to control crop-associated weeds (Cheema et al., 2003; Hong et al., 2004; Wazir et al., 2011; Farooq et al., 2013). The allelopathic potential of weeds varies from species to species (Hamayun et al., 2005; Zohaib et al., 2014a), with concentrations of allelochemicals (Zohaib et al., 2014b) and different plant parts of the same species showing differential allelopathic potential (Aziz et al., 2008). Aquatic weeds might also be used to suppress the growth of arable weeds, due to their strong allelopathic potential. The allelopathic potential of different aquatic weeds has been given in Table 1. Only a few examples are available in the literature to explore the influence of aquatic weeds in controlling weeds associated with field crops. Growth inhibitory effects of *A. philoxeroides* (one of the important weed in aquatic ecosystems and anaerobic rice) have been reported on barnyard grass (*E. crus-galli*) (Liuqing et al., 2007), which is a common weed of rice crops. Inhibitory effects were more significant on the root growth of *E. crus-galli* and grew by increasing the dose of *A. philoxeroides*. Quazi and Khan, (2010) stated that *A. polygonoides* extracts inhibited the growth of *P. hysterophorus* (a very troublesome and common invasive weed). The suppressive effect was due to the allelochemicals commonly found in *Alternanthera* species (Tanveer et al., 2013). However, it is also important to explore the allelopathic effects of other aquatic weeds to control weeds in field crops; it might prove a cheap and organic source to control weeds for a sustainable crop production. The use of herbicides to control weeds is considered not appropriate for a sustainable crop production due fast increasing herbicide resistance problem and harmful side effects of herbicides on the environment (Grin, 2010; Duke, 2012). Allelopathic extracts and residues of many terrestrial weeds and crops have been already proved very successful to control weeds in field crops (Weston and Duke, 2003; Xuan et al., 2005; Macías et al., 2007). The production of arable weeds for allelopathic residues and extracts in crop fields is not preferred because they create huge losses to crop yield and quality (Sheppard et al., 2006). Therefore, aquatic weeds that are economically considered useless or harmful to the aquatic ecosystem can be successfully used as a cheap source of aqueous extracts and as an allelopathic mulch to control weeds in field crops. Furthermore, the allelopathic effects of aquatic weeds might be more inhibitory and severe on terrestrial weeds, due to the lower adaptability of terrestrial weeds to aquatic weeds allelopathy (Reigosa et al., 1999). To understand the real picture of the aquatic weed allelopathic potential in controlling weeds in field crops, the measurement of concentration ranges of different aquatic weed water extracts on specific terrestrial weeds would require to be evaluated by using detailed bioassays, similarly to Jin et al. (2003), Abbas et al. (2014) and Mehmood et al. (2014). Aquatic weeds allelopathy may also be used to control algae on a sustainable basis, because herbicide resistance has been reported against most herbicides, due to their repeated use to control algae in aquatic ecosystems (Garcia-Villada et al., 2004; Cooke et al., 2005; Lopez-Rodas, 2007).

The allelopathic influence of plants on agriculture crops has been considered important to cope with the issues of food security, as it is involved in the decrease of food production. This review led to conclude that aquatic weeds have significant inhibitory effects on field crops, by reducing their germination and growth, which may lead to yield reduction. Moreover, aquatic weeds are involved in influencing soil chemical characteristics and nutrient availability through the release of allelochemicals into soil. The selectivity of receiver plants to allelochemicals released by aquatic weeds may lead to a change in the population and community structure of an ecosystem. In addition, a higher allelopathic potential of aquatic weeds increases the success to invasion and dominance of these weeds. The strong allelopathic potential of aquatic weeds due to the lower adaptability of arable weeds to aquatic weed allelopathy can be used as an organic, sustainable, environment-friendly and cheap source to control arable weeds in field crops. However, the replacement of chemical weed control is possible; that has emerged as a challenge, due to herbicide resistance and their harmful effects on the environment. Research efforts should be focused on screening more allelopathic aquatic weeds and evaluating their potential to control arable weeds in an agroecosystem. Understanding how to use aquatic weeds allelopathy would be an incandescent direction to achieve sustainability in crop yields, a sustainable weed control, reduced weed invasions and economic stability.

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