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Allelopathic activity of crop residues against noxious weeds: a review with particular emphasis on wheat residues

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Abstract Recently, field crops with allelopathic activity have gained overwhelming importance in overcoming the adverse effects of chemical herbicides on the environment and the increasing weed resistance to herbicides. Among the many cover crops studied for their allelopathic activity, wheat has exhibited strong allelopathic activity against a wide range of weed species, as reported in the previous literature. Several previous studies have focused on identifying wheat allelochemicals responsible for the weed suppression effect. The current review represents details about the most critical and influential chemical groups, including benzoxazinoids and phenolic compounds. In addition, several methods have been reported to exploit wheat's ability to combat weeds, including growing wheat in a crop rotation, applying wheat residues as soil mulch, or exposing weeds to wheat aqueous extract. A general background is also provided about allelopathy and allelochemicals; their concept, importance, chemical groups, mode of action and environmental impacts.
Keywords: *Triticum aestivum*, allelopathy, allelochemicals, phenolics, benzoxazinoids, weed control, aqueous extract

INTRODUCTION:

With the massive population growth worldwide, the rate of famine and the human need for food has consequently increased. Targeting higher yield production was associated with adopting new agricultural technologies markedly noticed in the late 1960s. This was termed the “green revolution” referring to the increased agricultural production at that time. Subsequently, many new technologies associated with the green revolution, primarily synthetic agrochemicals, have seriously negatively impacted the environment and biodiversity. Among the highly dangerous agrochemicals, pesticides have acute chronic toxicity even at low levels in addition to being persistent in the ecosystem. These adverse effects are noticeably exaggerated in developing countries with the lack or inefficiency of safety precautions in pesticide application (FAO 2017). In addition, overexploitation of chemical pesticides causes pest resistance and a decreasing response with repeated application of such substances.

To avoid or at least alleviate the adverse effects of synthetic pesticides, recent research work has focused on finding safe and eco-friendly alternatives for synthetic pesticides and herbicides as a fundamental component of sustainable agriculture. Natural chemicals produced by plants provide a great opportunity in the field of integrated management of pests and weeds. The release of chemicals by plants to defend themselves is called allelopathy. Exploiting this phenomenon has a wide range of applications and several benefits. Allelopathy represents an efficient biological method to combat weeds in crop production with no risk from the evolution of herbicide resistance in weeds (Anjum & Bajwa 2005, Cheema & Khaliq 2000, Heidarzade et al 2010).

Some noxious plants grow in undesired places, which are known as weeds. They have a negative impact on the yield and quality of main crop plants and consequently lead to large financial losses (Cheng & Cheng 2015, Wato 2020). Therefore, weeds are considered one of the foremost significant issues in agricultural production that reduce crop yield, especially in organic farming systems (Lemerle et al 2001, Petrova et al 2015).

It has been reported that the loss in crop yield caused by weeds reaches up to 25% in developing countries. To compensate for that high loss, the application of herbicides and other pesticides has recently increased (Lam et al 2012). Despite the efficiency of herbicides in combating weeds, continuous use of elevated concentrations of herbicides has triggered a severe problem of weed resistance against many herbicides (Fishel 2007). Moreover, herbicides represent a danger to the environment due to their negative impact on the soil, water and air, which indirectly threaten human health through their impact on food safety. (Eisler 2000, Macías et al 1998). The risks recently raised because of the overdependence and irrational use of herbicides, much attention has been devoted to the impact of herbicides on human health and the surrounding environment, in addition to investigating potential eco-friendly natural alternates for weed control. Of these alternatives, plant extracts with allelopathic activity are suggested as efficient, cheap and safe substances (Alsaadawi et al 2019, Uremis et al 2009).

Wheat (*Triticum aestivum*) is considered a worldwide staple food. It contains a crucial supply of carbohydrates and several other minerals and vitamins. In addition, it is the main ingredient in several foods. Wheat is an allelopathic crop that may be used for weed management. The allelopathic impact of wheat has been studied concerning its use as green manure/straw. Wheat suppresses weed growth thanks to the physical impact and the production of allelochemicals. The discharge of allelochemicals from living wheat plants has also been documented by several authors, such as Pethö (1992). The allelopathic potential of wheat can contribute to weed management in an eco-friendly way in different cropping systems (Jabran et al 2015, Wu et al 2003).

Therefore, the current review provides details about previous efforts done so far by researchers to elucidate the allelopathic potential of botanical extracts against weeds, with particular emphasis on wheat residues as a good example. This subject will raise public awareness about conserving the environment and environmental sustainability, which is in line with the Kingdom of Saudi Arabia's vision 2030 where sustainability is at the heart of everything.

1. Allelopathy: concept and background

Allelopathy is a natural phenomenon that occurs in both aquatic and terrestrial environments (Żak et al 2012). Thanks to

Molisch, the term allelopathy was defined for the first time in 1937 as the chemical interaction among plants. Many famous researchers in the field of allelopathy have considered the definition of Molisch, such as Rice (2013). The word allelopathy comes from the two Greek words ‘allelon’ and ‘pathos’, meaning ‘mutual harm’ or ‘suffering’. A more general definition of allelopathy includes any mutual effect between two plants, whether positive or negative. This effect occurs in response to certain biochemicals released from plant parts, which are known as allelochemicals affecting different aspects of plant ecology including occurrence, growth, plant succession, the structure of plant communities, dominance, diversity, and plant productivity (El-Ghit 2016, Rice 2013, Singh et al 2001). Moreover, allelochemicals may include any secondary metabolites produced by microorganisms that negatively or positively affect agricultural and biological systems according to the definition of allelopathy by the International Allelopathy Society (Torres et al., 1996). From the 1990’s, allelopathic research shifted from merely laboratory work to pot culture and field studies (Einhellig 1995, M'barek et al 2018).

The historical account of research on allelopathy was discussed comprehensively by Rice (1984), with elaborated details about the mutual relationship between higher plants and higher plants, higher plants and microorganisms, and microorganisms and microorganisms. According to Willis (1997), the historical development of allelopathy could be divided into 3 phases; the first is the de Candolle Phase: The period of the late 18th and early 19th century, especially between 1785 and 1845. The second is the Pre-Molisch Phase: The period at the beginning of the 20th century (from 1900-1920) known by the work of Pickering and Schreiner. Moreover, the third is the Post-Molisch Phase: 1937 onwards, which could progress since 1960 (Willis 1997). Recently, however, noticeable advancement has been achieved in this subject thanks to the efforts of scientists and the raised awareness of the whole community about the importance of replacing hazardous agricultural chemicals pesticides with eco-friendly natural ones (Singh et al 2001).

2. Allelochemicals

2.1. Definition and concept

The term ‘allelochemicals’ refers to chemical compounds released by the plant and are responsible for the mutual effect with other organisms known as allelopathy (Whittaker & Feeny 1971). Allelochemicals, hence, are directed from one plant known as the ‘donor’ towards another organism referred to as a ‘target or acceptor’. Donor plants produce these chemical substances as secondary metabolites and release them to the surrounding environment by root exudation, leaching from aboveground parts, and volatilization and/or decomposition of plant material (Cheng & Cheng 2015, Rice 2012, Soltys et al 2013). Previous studies revealed that chemical compounds triggering allelopathic effects are miscellaneous, though they could be classified into 14 categories according to Rice (2013) as illustrated in Fig 1.

As clearly illustrated in Fig. 1., most of the chemicals with allelopathic activity are secondary metabolites. Allelochemicals have particular importance for cereals and some other field crops in their defense against biotic and abiotic stresses. Of the many allelochemical groups, phenolic compounds are commonly produced by most of these field crops as presented in Fig. 2. In addition to phenolics, other chemical groups have been reported by (Jabran 2017a) and references therein, which included benzoxazinoids in wheat, maize and rye, glucosinolates in Brassicaceae plants, momilactones in rice, alkaloids in barley, sorgoleone in sorghum and terpenes in sunflower.

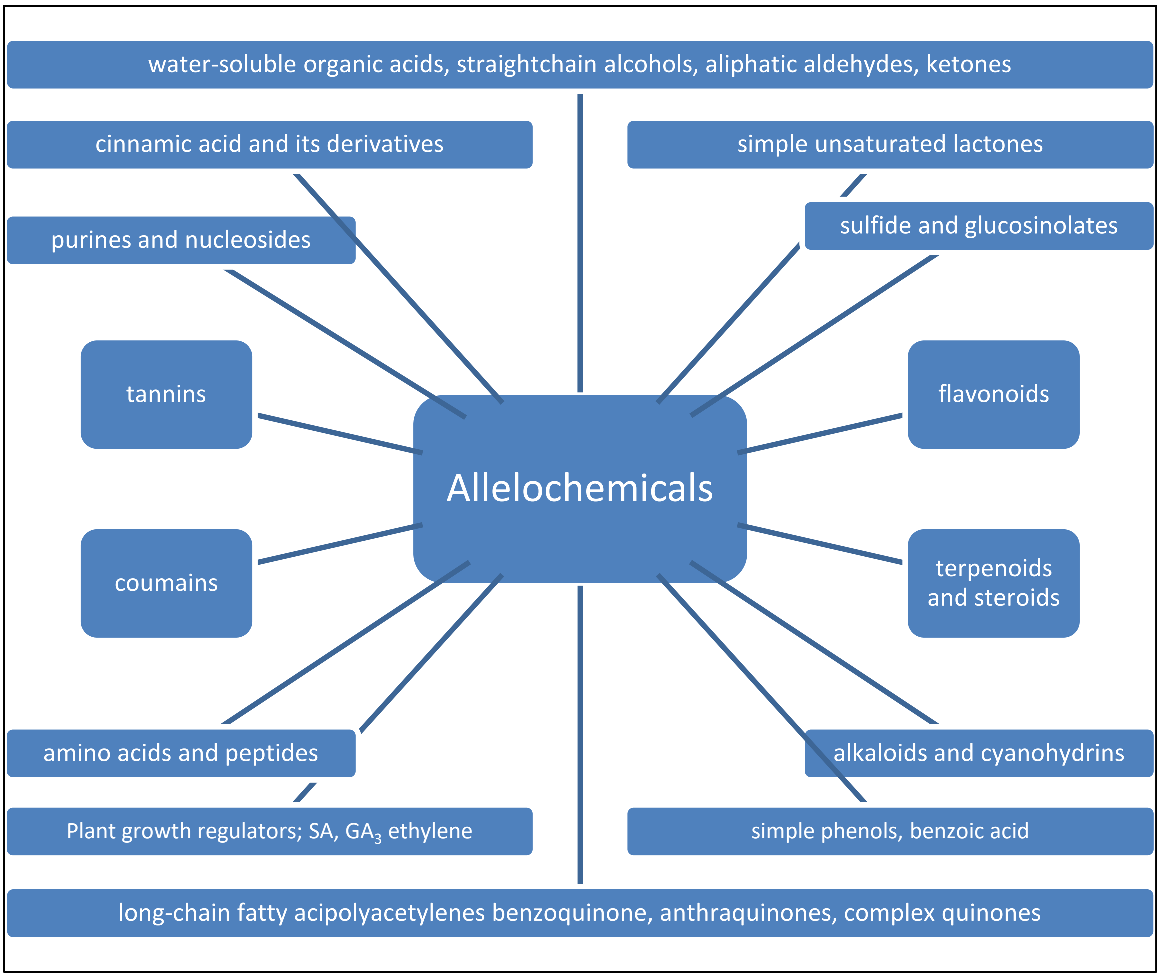


Fig. 1. Illustration showing allelochemical categories according to Rice (2013)

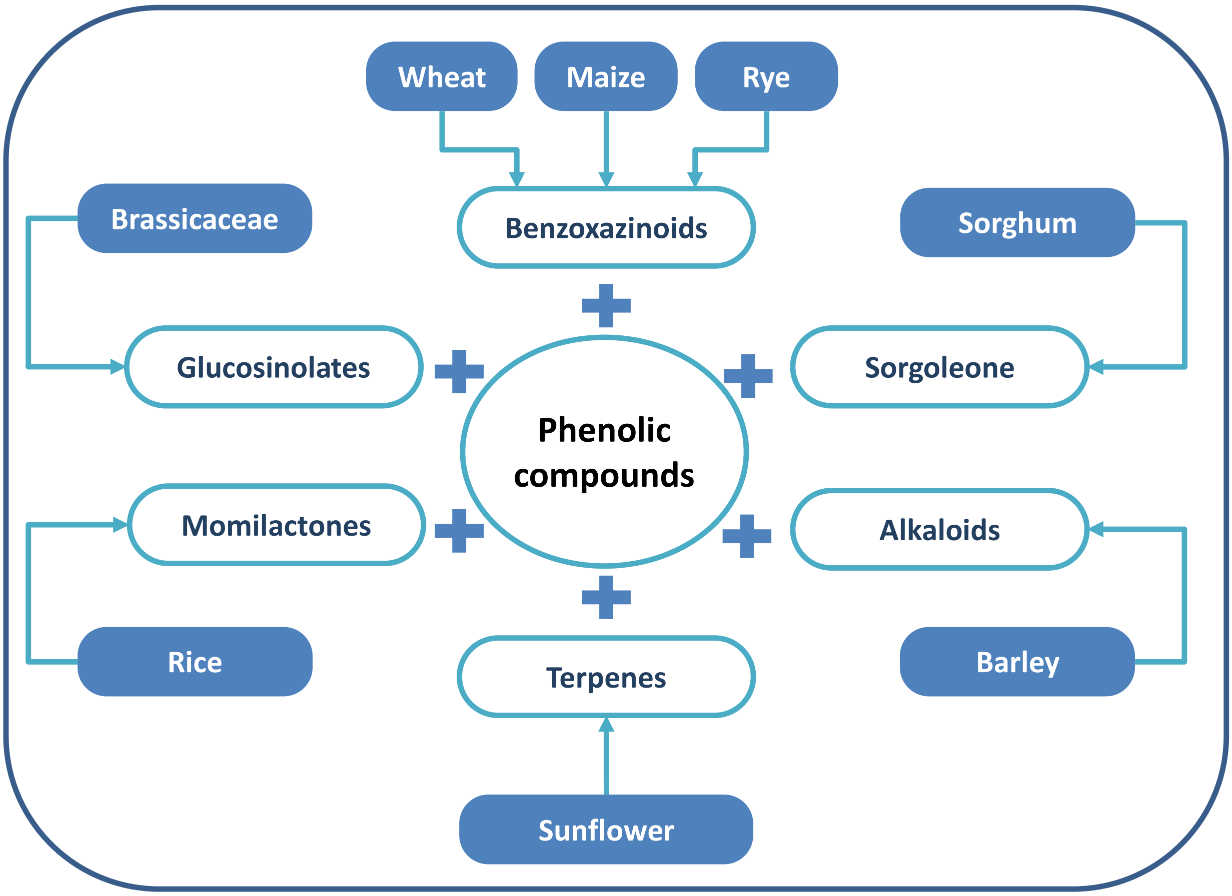


Fig. 2. A summary of important allelochemicals/allelochemical groups reported in important allelopathic crops; adopted from Jabran (2017a)

Different plant genotypes produce different types of secondary metabolites with varying concentrations depending on environmental conditions during their growth. Thus, it is crucial to control all the factors related to the plant itself and the surrounding environment in order to obtain the desired allelochemicals with a specific allelopathic effect. Factors associated with the plant include the plant species or genotype, its growth stage and the plant part. The environmental factors, however, may be associated with the soil (soil fertility, soil moisture, etc..) or the climate (relative humidity, day length, temperature, etc..) (de Albuquerque et al 2011, Kruse et al 2000, Quader et al 2001). Some scientists such as An et al (2008) raised the question of whether environmental factors affect the type of allelochemicals produced by a specific plant. They ensured that the chemicals produced by a plant under the favored environmental factors are found in the plant under normal conditions but may be inactive. Some environmental factors, however, put the plant under stressful conditions, which encourages the plant to produce the same allelochemicals but in dramatically higher concentrations to adapt to the stress conditions. Examples of stressful environmental factors include abnormal radiation (del Moral 1972), mineral deficiencies (Lehman & Rice 1972), water deficits (Gilmore 1977), temperature extremes (Koeppe et al 1970), and pathogen and predator attacks (Woodhead 1981).

2.2. Importance of allelochemicals

Although plant secondary metabolites are not necessary for plant growth since they are not involved in nutrition and reproduction, they have particular importance in plant protection against biotic and abiotic stress factors. Plants defend themselves by several means, of which allelochemicals are of particular importance (Bais et al 2003). Flavonoids represent a clear example of defensive allelochemicals used by plants to protect against UV radiation (McClure 1975). Phenolics have an evident effect on pathogenic microorganisms and insects (Friend 1979). A plant may be obliged to inhibit the growth of other plants to survive under unfavored conditions for plant growth, such as drought or nutrient deficiency (Kuo et al 1989). The effect of allelochemicals may exceed our imagination, where the plant might kill a few cells of its own if it is under the attack of pathogens in order to restrict the pathogen and reduce the damage (Farkas & Kiraaly 1962).

2.3. Environmental changes caused by allelochemicals

Many of the allelochemicals released from the plant into the environment are water-soluble. Upon their discharge to the environment by any means, whether exudation or volatilization from living plant parts or decomposition of fallen parts and residues, they induce a wide range of biological effects. Exploiting such effects in agriculture and weed management has been a focal point of several studies for decades (Anaya et al 1990, Macías et al 2006). The herbicidal efficacy of many allelochemicals has been proved from bioassays on a lab-scale by several researchers. However, when applied to the soil, many of these chemicals that showed potential allelopathic activity in the lab bioassay do not show inhibitory effects (Cheng & Cheng 2015). Several researchers, such as Belz (2007) and Kaur and Kaushik (2005), described the effect of allelochemicals in the soil as ‘unknown’ and attributed its ambiguous effect on the soil environment in terms of its chemical, physical and biological properties.

When the donor plant is considered invasive in a specific location, announced environmental changes are evident due to the allelochemicals produced by this plant. (Weiner 2001). These changes directly or indirectly affect other plants at the plant community or ecosystem level (Batish et al 2001, Buehler & Rodgers 2012, Wardle et al 2011). Allelochemicals also trigger changes at the soil level. Several studies elucidated the changes in soil nutrient concentration in response to allelochemicals such as phenolic compounds. Explanations provided for the occurred changes suggested that phenolic compounds, together with specific nutrients, form complexes making these nutrients unavailable to the plants, while the availability of other nutrients, such as phosphorus, increases due to the competition with the sites of immobilization of this nutrient in the soil organic matter, clay particles, soluble aluminum, iron or manganese (Appel 1993).

2.4. Modes of action of allelochemicals

It has been stated that the allelopathic effect of allelochemicals could be described as a physiological effect rather than a mode of action. Some physiological effects of specific allelochemical groups have been stated in the literature, such as inhibition of mitochondrial function and PSII induced by sorgoleone produced by sorghum crop (Alsaadawi & Dayan 2009, Einhellig et al 1993, Rasmussen et al 1992), decrease in the regeneration of root cap cells, root elongation, number of lateral roots and chlorophyll synthesis induced by DIBOA and BOA from rye crop (Barnes & Putnam 1987, Burgos et al 2004), inhibition of cell division, photosynthesis, respiration, and nutrient uptake disruption of the cell membrane, hormones, and protein synthesis induced by phenolic compounds from several plant species (Li et al 2010). The possible modes of action of allelochemicals were elucidated in detail by Rice (1984) in his book, which could be summarized in the following points:

- Impacts on cell division, elongation, and ultrastructure
- Impacts on hormone-prompted growth
- Impacts on membrane permeability
- Impacts on nutrients uptake
- Impacts on available P and K in growth media and soils
- Impacts on stomatal opening and photosynthesis
- Impacts on respiration
- Reduction of protein synthesis
- Impacts on lipid and organic acid metabolism
- Possible constrain of porphyrin synthesis
- Effects on internal water relations and xylem elements
- Performance of specific enzymes
  - Pectolytic enzymes
  - Cellulase
  - Catalase and peroxidase
  - Phosphorylases
  - *p*-Cystathionase (cystathionine (3-Lyase)
  - Phenylalanine ammonia-lyase
  - Sucrase (invertase)
  - Other enzymes

Allelochemicals are most effective in the seedling stage of many plant species. As weeds grow, they become less susceptible to allelochemicals released in their rhizosphere. To achieve a direct effect, a cultivar must release allelochemicals in bioactive concentrations before the target weeds reach old age. Therefore, it is essential to understand the critical development stage, where the crop starts releasing allelochemicals and the critical sensitive stage of the target weeds (Olofsdotter 1998).

3. Application of Allelopathy in Weed Management

3.1. Hazardous weeds

The word weed denotes any plant, often wild, that grows in an undesirable spot (Wato 2020). Weed species represent about 3% of recorded plant species worldwide (Yang et al 2019). Examples of noxious weed species that invade field crops, especially wheat include *Avena fatua* L., *Phalaris minor* Retz., *Bromus* species, *Lolium* species, *Cirsium arvense* (L.) Scop., *Veronica* species, *Capsella bursa-pastoris* (L.) Medik., *Lamium* species, *Chenopodium album* L., *Galium* species, *Sorghum halepense* (L) Pers, *Cynodon dactylon* L. and *Rumex crispus* L. (Jabran 2017b, Petrova et al 2015). Weed plants survive and reproduce without the involvement of humans, causing a severe problem of cultivated agricultural lands, including fields and different types of gardens, which ultimately affect their production or aesthetic value (Oimbo et al 2018). Therefore, it is very important to apply an efficient strategy to prevent and combat weed spread. Prevention starts with the identification of weed sources, of which importation is considered a major source (Suominen 1979, Vilà et al 2004).

An estimation of the loss in crop yield caused by weeds was reported to be 35% in wheat, 37% in tobacco and about 28 to 29% in vegetables and fruits (Oerke 2006, Petrova et al 2015). This effect has been attributed to their aggressive competition with the crop since weeds grow, reproduce and acclimatize with the environment more efficiently than crops (Kim & Moody 1989). The completion becomes even higher when weeds germinate with or before the crop (Swanton et al 2015). Moreover, any delay in weeding beyond 20 days after emergence will ultimately result in uncorrectable severe yield losses (Sureshkumar et al 2016). Some weed species may not cause critical crop yield losses, yet they significantly affect crop quality (Swanton et al 2015). Some scientists describe the relationship between weeds and crops as complicated because it starts with the emergence of weeds sharing the same space assigned for the crop. The competition then becomes higher since weeds grow faster and hence have more ability to absorb nutrients and make use of moisture and light (Singh et al 2004, Wright et al 2001). As they grow, weeds become a host to many insects, nematodes and pathogenic microorganisms (Javald 2010).

3.2. Allelopathy and weed control

The phenomenon of allelopathy has been successfully utilized recently in the field of weed management as an eco-friendly alternative to synthetic hazardous chemical herbicides. As previously aforementioned in this report, botanical extracts comprise enormously diverse allelochemicals with varying modes of action in terms of weed control (Farooq et al 2013). Allelochemicals cause growth reduction by their interference with plant growth and development. In addition, they affect cell division, hormone biosynthesis, and mineral uptake and transport (Rizvi et al 1992), membrane permeability (Harper & Balke 1981), stomatal oscillations, photosynthesis (Einhellig & Rasmussen 1979), respiration, protein metabolism (Kruse et al 2000) and plant water relations (Rice, 1984).

Several researchers, such as Farooq et al (2013), have proved the efficiency of plant aqueous extracts in suppressing weed growth. Sorghum water extract is a famous example of an efficient extract widely used as a natural herbicide. In a study by Cheema and Khaliq (2000), sorghum aqueous extract suppressed the growth of four weed species in wheat crop by inhibiting weeds' density and dry weight. To increase the efficiency of plant extracts, some researchers suggest incorporating them with lower herbicides at lower doses. This strategy showed promising results as the applied dose of the synthetic herbicide could be reduced to half the recommended one if combined with the plant extract (Farooq et al 2013).

The allelopathic activity of plant material is not restricted to their extracts as crop residues induce allelopathic activity when incorporated with the soil or applied as soil mulches (Khaliq et al 2010). Wheat straw, for instance, showed allelopathic activity against different weed species when used as a soil mulch at a rate of 4-8g/kg soil, as pointed out by Khaliq et al (2011) and Jabran (2017b). Wheat straw mulch suppressed weed growth by inhibiting germination and different vegetative growth patterns including synthetic pigments, protein, leaf and root growth, and biomass.

Thus, the potential allelopathic activity of such natural plant extracts provides a safe and efficient substitute for hazardous chemical herbicides or time-consuming and inefficient mechanical methods of weed management (Farooq et al 2013).

3.3. Allelopathy and protection of the environment

Among all the pests threatening the agricultural system, weed control is a great challenge due to its severe impacts on crop productivity. This problem becomes even worse if farmers lack the proper method for weed control or in organic agricultural systems where limited options are allowed to ensure the safety of the final product (Melander et al 2018, Pimentel et al 2005). The reported volumes of applied herbicides are far more than insecticides and fungicides (Köhler & Triebskorn 2013). Most conventional herbicides are synthetic chemicals, with only 8% derived from natural sources. With increased awareness about the dangers of these compounds, the percentage of active ingredients with natural origin reached 70% in newly registered pesticides by USEPA (Cantrell et al 2012).

Although herbicides are essential to alleviate the adverse effects of weeds on crop productivity, they pose severe risks to the surrounding environment and living organisms (Nikneshan et al 2011). Humans are directly and indirectly affected by these environmental problems which have been associated with countless health problems. In addition, the efficiency of synthetic herbicides against specific weed species is significantly reduced with repeated application because of the incidence of weeds' resistance to these compounds (Heidarzade et al 2010). To face the fast development of herbicide resistance in weeds, nonstop modification of herbicide groups or their mode of action is required (Elqahtani et al 2017, Farooq et al 2020).

Several researchers consider allelopathy a promising efficient method for the widely applied hazardous chemical herbicides and a potential cure for the damage caused by these compounds for decades to the ecosystem. It is a milestone towards the sustainable development of agricultural production and ecological systems, which became a focal research point of scientists in the field of allelopathy (Cheng & Cheng 2015, Han et al 2013, Li et al 2010, Sangeetha & Baskar 2015). The herbicidal activity of allelopathic compounds has particular importance in organic farming, where there are restrictions on the use of the majority of chemical herbicides conventionally involved in weed management (Kruse et al 2000). Compared with herbicides, allelochemicals have no or insignificant negative impact on the environment, especially water and soil, allowing for the safe recycling of these resources (Macías et al 2003). Although the efficacy and specificity of many allelochemicals are limited, the wide variety of chemical groups and compounds with potential allelochemical activity allow for screening and developing endless novel herbicide modes of action (Bhadoria 2011, Dayan & Duke 2014). However, detailed and comprehensive studies are required to prove and elucidate the herbicidal efficacy of the tested compounds since their effects vary with the tested variety of the receptor plant, type and concentration of the extract, growth stage of the used part of the donor plant in addition to the environmental conditions where the donor plants grow (Jabran 2017a, Singh et al 1999).

4. Allelopathy of wheat crop

4.1. Wheat (*Triticum aestivum*)

Wheat (*Triticum aestivum* L.) belongs to the Triticeae tribe. It is one of the most crucial field crops for the global economy and food security. It is ranked on the top list of cereal crops and rice and maize in terms of the produced quantities of edible grains, reaching 729 million tons in 2014, according to FAO reports. The nutritional value of wheat is attributed to its high content of carbohydrates, proteins, minerals and vitamins. Wheat flour is mainly used to produce bread and pasta. In addition, wheat straw and other residues are used as animal feed and organic manure as well as to manufacture several byproducts (de Albuquerque et al 2011, Jabran 2017b). Furthermore, there has been growing evidence from the published literature that wheat residues have potential allelopathic activity against weeds. Several studies have elucidated the nature of the active constituents in wheat residues and their mode of action in weed management (Pethö 1992).

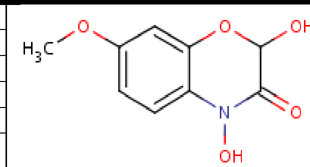
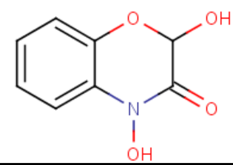
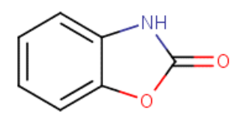
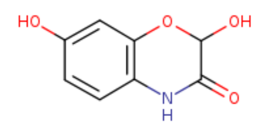
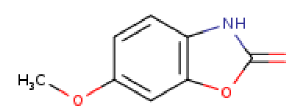
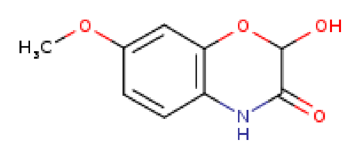
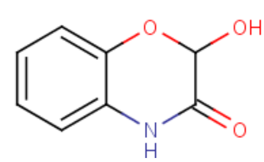
4.2. Wheat allelochemicals

As previously mentioned, the active plant constituents with allelopathic activity are mainly secondary metabolites belonging to various categories, including phenolics, terpenoids, alkaloids, coumarins, tannins, flavonoids, steroids and quinines. The reported allelopathic activity of wheat has been associated with a broad set of allelochemicals. These chemicals belong mainly to phenolics, benzoxazinones, hydroxamics, and short-chain fatty acids. It has been stated that the type and concentration of allelochemicals in wheat tissues vary among wheat varieties suggesting varying allelopathic capacity (Macías et al 2005, Wu et al 2001a, Wu et al 2001b).

4.2.1. Benzoxazinones & hydroxamic acids

Benzoxazinones, especially hydroxamic acids, are among the crucial allelochemicals reported in wheat and other cereal crops in the previous literature. Information about various hydroxamic acids previously isolated from wheat is summarized and provided in Table 1. These include DIMBOA, BOA (Mathiassen et al 2006), MBOA, HMBOA, HBOA (Krogh et al 2006), DIBOA and DHBOA (Huang et al 2003). All these are benzoxazine, of which DIBOA and DIMBOA are hydroxamic acids with a hydroxyl group on the nitrogen atom at position 4 (Huang et al 2003). According to Krogh et al (2006), the dominant allelochemicals in wheat leachates are comprised of MBOA, in addition to both HMBOA and HBOA with lower concentrations.

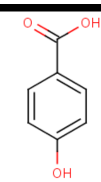
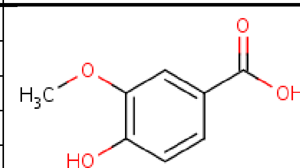
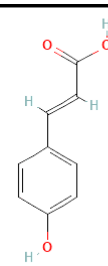
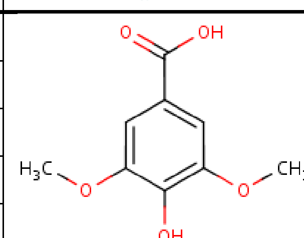
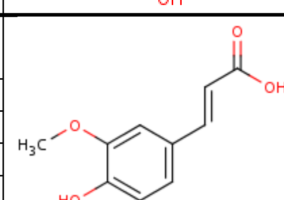
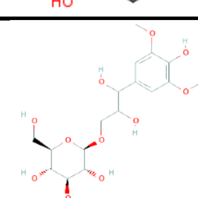
Table 1. Chemical structure and attributes of benzoxazinones (DIMBOA, DIBOA and BOA, MBOA, HMBOA and HBOA) isolated from wheat and other cereals (ChEBI 2022, PubChem 2022).

no	Compound Attributes		Structure
1.	Name	**DIMBOA**	
	IUPAC name	2,4-Dihydroxy-7-methoxy-1,4-benzoxazin-3-one	
	Synonym	2,4-Dihydroxy-7-methoxy-2H-1,4-benzoxazin-3(4H)-one	
	Formula	$C_9H_9NO_5$	
	MW	211.17	
	CAS No.	15893-52-4	
2.	Name	**DIBOA**	
	IUPAC name	2,4-Dihydroxy-1,4-benzoxazin-3-one	
	Synonym	2,4-Dihydroxy-2H-1,4-benzoxazin-3(4H)-one	
	Formula	$C_8H_7NO_4$	
	MW	181.15	
	CAS No.	17359-54-5	
3.	Name	**BOA**	
	IUPAC name	3H-1,3-benzoxazol-2-one	
	Synonym	benzoxazolin-2-one	
	Formula	$C_7H_5NO_2$	
	MW	135.12	
	CAS No.	59-49-4	
4.	Name	**DHBOA**	
	IUPAC name	2,7-Dihydroxy-2H-1,4-benzoxazin-3(4H)-one	
	Synonym	2,7-dihydroxy-4H-1,4-benzoxazin-3-one	
	Formula	$C_8H_7NO_4$	
	MW	181.15	
	CAS No.	69804-59-7	
5.	Name	**MBOA**	
	IUPAC name	6-methoxy-3H-1,3-benzoxazol-2-one	
	Synonym	6-methoxy-2-benzoxazolinone (Coixol)	
	Formula	$C_8H_7NO_3$	
	MW	165.15	
	CAS No.	532-91-2	
6.	Name	**HMBOA**	
	IUPAC name	2-hydroxy-7-methoxy-4H-1,4-benzoxazin-3-one	
	Synonym	2-Hydroxy-7-methoxy-2H-1,4-benzoxazin-3(4H)-one	
	Formula	$C_9H_9NO_4$	
	MW	195.17	
	CAS No.	17359-53-4	
7.	Name	**HBOA**	
	IUPAC name	2-hydroxy-4H-1,4-benzoxazin-3-one	
	Synonym	2-hydroxy-1,4-benzoxazin-3-one	
	Formula	$C_8H_7NO_3$	
	MW	165.15	
	CAS No.	23520-34-5	

4.2.2. Phenolic acids & phenolic glycosides

There is concrete evidence that phenolic compounds are the most widespread water-soluble allelochemicals that pose significant effects on mutual plant interaction, including allelopathy (Batish et al 2002). Several phenolics have been isolated and identified from wheat and other cereals, mainly phenolic acids and phenolic glycosides. Table 2 presents a list of phenolic acids isolated from wheat, including *p*-hydroxybenzoic, vanillic, *p*-coumaric, syringic and ferulic acids (Lodhi et al 1987, Wu et al 2001b) as well as the phenolic glycoside Syringoylglycerol 9-O-beta-Dglucopyranoside (Nakano et al 2006).

Table 2. Chemical structure and attributes of benzoxazinones (DIMBOA, DIBOA and BOA, MBOA, HMBOA and HBOA) isolated from wheat and other cereals (ChEBI 2022, PubChem 2022).

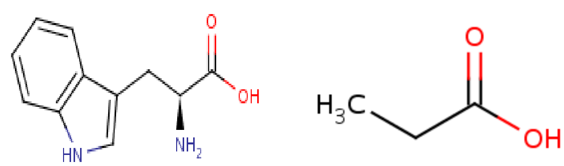
no	Compound Attributes		Structure
1.	IUPAC name	p-hydroxybenzoic acid	
	Synonym	Benzoic acid, 4-hydroxy-	
	Formula	$C_7H_6O_3$	
	MW	138.12	
	CAS No.	99-96-7	
2.	IUPAC name	4-hydroxy-3-methoxybenzoic acid	
	Synonym	Vanillic acid	
	Formula	$C_8H_8O_4$	
	MW	168.15	
	CAS No.	121-34-6	
3.	IUPAC name	(*E*)-3-(4-hydroxyphenyl) prop-2-enoic acid	
	Synonym	*p*-coumaric acid	
	Formula	$C_9H_8O_3$	
	MW	164.16	
	CAS No.	7400-08-0	
4.	IUPAC name	4-hydroxy-3,5-dimethoxybenzoic acid	
	Synonym	Syringic acid	
	Formula	$C_9H_{10}O_5$	
	MW	198.17	
	CAS No.	530-57-4	
5.	IUPAC name	(*E*)-3-(4-hydroxy-3-methoxyphenyl) prop-2-enoic acid	
	Synonym	Ferulic acid	
	Formula	$C_{10}H_{10}O_4$	
	MW	194.18	
	CAS No.	537-98-4	
6.	IUPAC name	(2*R*,3*R*,4*S*,5*S*,6*R*)-2-[2,3-dihydroxy-3-(4-hydroxy-3,5-dimethoxyphenyl) propoxy]-6-(hydroxymethyl)oxane-3,4,5-triol	
	Synonym	Syringoylglycerol 9-O-beta-Dglucopyranoside	
	Formula	$C_{17}H_{26}O_{11}$	
	MW	406.4	

	CAS No.	---	

4.2.3. Amino acids

L-tryptophan was isolated from oat (Kato-Noguchi et al 1994), aqueous leachate of wheat straw (Nakano et al 2006) and wheat barn extract (Nakano 2007) as allelochemicals with potential inhibitory activity against the growth of various plant species. The chemical structure and some essential attributes of L-tryptophan are shown in Fig. 1.

A B



L-tryptophan Propionic acid

Fig. 1. Chemical structure of compound A: L-tryptophan ((2*S*)-2-amino-3-(1*H*-indol-3-yl)propanoic acid) and B: Propionic acid (Propanoic acid; Propionic acid)

4.2.4. Short-chain fatty acids

Phytotoxicity of water-soluble short-chain fatty acids isolated from wheat straw extracts has been reported by several researchers. Tang and Waiss (1978) isolated and identified major compounds from the toxic fractions of the aqueous extract of decomposing wheat, which included acetic, propionic (Fig. 1), and butyric acids in addition to traces of isobutyric, pentanoic, and isopentanoic acids. The authors stated that they could not detect any phenolic acids in their extract.

4.3. Allelopathic activity of wheat crop

4.3.1. Wheat allelopathy against other crops

Wheat has caused allelopathic inhibition to the growth and yield of crops such as rice, barley, rye, cotton and soybean. Wheat straw was also allelopathic to several forage crops, including sorghum, sunflower, pearl millet, cluster bean, cowpeas, and mulberry (Narwal et al 1997). This effect was further proved by Lodhi et al (1987) on wheat and cotton seeds. Seed germination and seedling growth of both crops were inhibited when exposed to the aqueous extracts of wheat mulch and soil from the wheat field. They attributed the allelopathic effect to isolated phenolic acids, including ferulic, *p*-coumaric, *p*-OH benzoic, syringic, and vanillic acids.

Wheat was particularly useful among the nine cover crops because it was easy to control chemically, provided good weed suppression, and was least inhibitory to the seedling establishment of main crops, including cucumber, soybean, snap bean, pea and corn maize (Weston 1990). Another study by Bai et al (2021) suggested that the extract from germinated wheat seeds could inhibit the growth of cucumbers by affecting the physiological and biochemical processes.

Wheat residue allelopathy has different unfavorable impacts on the growth of other crops depending on the wheat variety. The influence of surface-obtained wheat stubble on canola's emergence, growth, and yield was studied in field tests in southern New South Wales. The results of the trials showed that canola growth in surface-retained wheat stubble is poor (Bruce et al., 2005) . Chemical analysis indicated that leachate of wheat straw inhibited the root growth of lettuce and cress (Nakano et al 2006). Furthermore, Fatholahi et al (2020) showed that aqueous shoot extracts of all wheat genotypes suppressed the seedling growth of *Raphanus sativus* L. Also, Hozumi et al (1974) reported that aqueous extracts from wheat residues suppressed the growth of rice, barley and rye. Wheat residues were also allelopathic to the growth of soybeans (Herrin et al 1986). The allelopathic potential of 20 wheat cultivars has induced varying effects on the growth of soybean cv. Dare growing in soils that include 2% wheat straw residue (Collins & Caviness 1978). Among the wheat type cv. Blueboy had the least allelopathic effect (Wu et al 2001b).

It has been stated that sensitivity to wheat residue allelopathy varies with crops. For example, Putnam et al. (1983) reported that the growth of cabbage, corn, cucumber, lettuce, pea, and snap bean had differential responses to wheat residues and hypothesized that larger seeded crops were more tolerant than smaller seeded species. Similarly, Dias (1991) found that wheat, oats, and subterranean clover differed in their responses to decomposing wheat straw and associated soil, with the primary stimulation of subterranean clover and the inhibition of cereals.

Variation is also present among genotypes of the same crop. For example, Hicks et al (1989) screened 11 varieties of cotton for the ability to tolerate the inhibitory effects of wheat straws in laboratory bioassays and greenhouse studies. A tolerant variety, cv. Paymaster 404, was identified and used in field experiments. Cotton emergence was reduced by an average of 9% for cv. Paymaster 404 and 21% for cv. Acala A246. Soybean varieties were also found to differ significantly in their tolerance to the allelopathic effects of wheat residues with cv. Davis and cv. Centennial being the most tolerant and cv. Forrest the least (Caviness et al 1986).

4.3.2. Wheat allelopathy against weeds

Several noxious weed species have been reported to interfere with weed crops. Of these species, the most important and widely include *Avena fatua* L., *Phalaris minor* Retz., *Bromus rubens* L., *Lolium* species, *Cirsium arvense* (L.) Scop., *Veronica* species, *Capsella bursa-pastoris* (L.) Medik., *Lamium* species, *Chenopodium album* L., *Galium* species, *Sorghum halepense* (L) Pers. *Chenopodium album* L, *Cynodon dactylon* L. and *Rumex crispus* L. (Jabran 2017b, Petrova et al 2015). The irrational use of herbicides caused the development of resistance and shifts in weed populations, the emergence of a substitution weed flora, substantial environmental pollution and subsequent health hazard (Scavo & Mauromicale 2020). Nowadays, the increasing costs in the agricultural sector, increasing public concern about the widespread use of herbicides and the development of non-chemical methods of weed control programs are alerting management (Sarker et al 2022).

Recently, field crops with allelopathic activity have gained overwhelming importance in overcoming the adverse effects of chemical herbicides on the environment and the increasing weed resistance to herbicides. Among the many cover crops studied for their allelopathic activity, wheat has exhibited strong allelopathic activity against a wide range of weed species, as reported in the previous literature (Belz 2007, Lemerle et al 1996, Olofsdotter et al 1997, Tursun et al 2018, Weston 1996).

Screening, selection, evaluation, and development of wheat cultivars with increased inherent competitiveness against herbicide-resistant weeds is a potential supplement to in-crop herbicide use and, in some cases, an alternative management strategy, particularly for organic producers (Yang et al 2020) . Therefore, the results indicated that growing weeds in high quantities between crops could affect the productivity rate of crops due to its allelopathic effects. The allelopathic compounds can be used as natural herbicides and other pesticides; they are less disruptive to the global ecosystem than synthetic agrochemicals (Chauhan et al 2022). Therefore, reducing herbicide use and herbicide-resistant weeds through allelopathy can be a sustainable strategy to combat the concerns of environmental degradation. Furthermore, allelopathic crop residues carry great potential as weed suppressers and soil quality enhancers (Ullah et al 2022).

Several methods have been reported to exploit the wheat ability to combat weeds, including growing wheat in a crop rotation, applying wheat residues as soil mulch, or exposing weeds to wheat aqueous extract (Pethö 1992). It has been found that the aqueous extract of wheat residues is allelopathic to several weeds and has consistently reduced weed emergence and growth (Wu et al 2001b). Narwal et al (1998) showed that wheat straw caused a 16.8% reduction in broad-leaved weeds. Under laboratory conditions, aqueous extracts from wheat straw are allelopathic against a broad spectrum of weed species (Liebl & Worsham 1983, Rambakudzibga 1991, Steinsiek et al 1980, Steinsiek et al 1982).

Crop residues can significantly affect weed growth and development by altering the soil's physical, chemical, and biological properties. Thus, allelopathy, expressed through the release of chemicals by plant or crop residues, has been suggested to be one of the possible alternatives for achieving sustainable weed management. Nowadays, experts focus more on utilizing various crop residues for weed management. Alteration of crop allelopathy can be a viable approach for sustainable weed management strategies. Generally, allelopathic interactions suppress weeds to a lesser extent than standard weed control limits. Moreover, combining allelopathic crop water extracts with reduced herbicide rates may lead to lower desirable weed control levels, resulting in decreased herbicide usage (Sarker et al 2021). Wheat residue allelopathy differs among varieties (Wu et al 2001b). In Australia, 38 wheat accessions were evaluated for residue allelopathy against annual ryegrass (*Lolium rigidum* Gaud.) by an aqueous extract bioassay (Wu et al 1998). Results showed that aqueous extracts of wheat residues significantly inhibited germination and root growth of ryegrass and that inhibition differed significantly between accessions. The inhibition for root growth ranged from 19.2% to 98.7%, and for seed germination, from 4.2% to 73.2%. The same set of wheat accessions was also employed to test a biotype of annual ryegrass resistant to herbicides of acetyl CoA carboxylase inhibitors (group A), acetolactate synthase inhibitors (B), photosystem II inhibitors (C), and tubulin formation inhibitors (D) (Wu et al 2001c). Results showed that aqueous wheat extracts significantly inhibited this resistant biotype's germination and root growth, with the germination being inhibited by 3.3% to 100%, depending upon accession. The allelopathic effects on ryegrass root growth ranged from 12% stimulation to 100% inhibition, compared to a control. The results suggest that wheat allelopathy might also have potential in managing herbicide-resistant weed species.

Thilsted & Murray (1980) found that the inhibition of *Amaranthus* spp. in wheat straw-mulched plots was approximately equivalent to that obtained with herbicides in straw-mulched and bare-soil plots. Banks & Robinson (1980) also reported that a straw mulch suppressed the growth of spiny amaranth (*Amaranthus spinosus* L.), tall morningglory [*Ipomoea purpurea* (L.) Roth], and volunteer wheat more than herbicides used on non-mulched areas. (Shilling et al 1985) claimed that wheat mulches had an allelopathic suppressive effect on some broadleaved weeds. The allelochemicals in wheat residues could kill weeds in the next crop sown into the mulched residues under no-till systems (Worsham 1984). Jobidon et al (1989a) demonstrated that water extracts of wheat straw inhibited propagule growth of the common forest weed red raspberry (*Rubus idaeus* L.) by 44%. This allelopathic effect was further verified in field experiments (Jobidon et al 1989b).

Wheat progenitors have also been screened for differential seedling allelopathy on the growth of wild oat (*Avena fatua* L.) and Indian hedge mustard (*Sisymbrium orientale* L.) (Abul & Adkins 1998). It was found that one out of 17 accessions of *Triticum speltoides* L. inhibited the root length of wild oat, and two out of 19 accessions inhibited the radicle length of Indian hedge mustard. An experiment was conducted with aqueous extracts of four wheat cultivars (Morvarid, Moghan, Tajan, and Arta). The study results showed that the least allelopathic effect was in Tajan cultivar and the most allelopathic effect was in Morvarid cultivar against wild mustard weed (Rezvani & Fazeli Kakhki 2021).

Crop rotation is a well-known practice in sustainable agriculture, which has proved its impact on weed control (Teasdale et al 2004). When an allelopathic crop is grown, the benefits of weed growth suppression become apparent in the following crop (Liebman & Dyck 1993). Examples of the inclusion of allelopathic crops in a rotation have been reported in the available literature. For example, growing sorghum or sunflower before wheat considerably reduced weed infestation in wheat crops (Einhellig & Rasmussen 1989, Farooq et al 2011).

In order to evaluate the allelopathic effect of wheat residue extracts, experiments were carried out on prostrate pigweed (*Amaranthus blituides*) and common lambsquarter (*Chenopodium album*). Results showed that extracts of wheat residue had an inhibitory effect on germination in both. Furthermore, results showed allelopathic effects of wheat residue could be used for weed management (Hosseini et al 2022). Allelochemicals from various wheat genotypes have been shown to inhibit the growth of selected weed species, including *Bromus japonicus*, *Chenopodium album*, *Portulaca oleracea*, *Avena fatua* and *Lolium rigidum* (Hussain et al 2022). In addition, Scavo et al (2022) research documented the allelopathic effects of selected durum wheat landraces on seed germination of two common weed species infesting wheat (*P. oleracea* and *S. media*).

5. Conclusions

Several previous researchers have elucidated the allelopathic potential of botanical extracts from crop residues, especially wheat, against weeds. Wheat has exhibited strong allelopathic activity against a wide range of weed species. Thus, special care has been devoted to identifying wheat allelochemicals responsible for weed suppression, where the most critical and influential chemical groups included benzoxazinoids and phenolic compounds. Several methods have been reported to exploit wheat's ability to combat weeds, including growing wheat in a crop rotation, applying wheat residues as soil mulch, or exposing weeds to wheat aqueous extract. In addition, mode of action and environmental impacts of the allelochemicals have been discussed in detail.

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النشاط الأليلوباثي لمخلفات المحاصيل ضد الحشائش الضارة: دراسة مرجعية مع التركيز بشكل خاص على مخلفات القمح

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مستخلص. في الآونة الأخيرة، ازدادت أهمية المحاصيل الحقلية ذات النشاط الأليلوباثي في التغلب على الآثار الضارة لمبيدات الحشائش الكيميائية على البيئة وزيادة مقاومة الحشائش للمبيدات. من بين العديد من المحاصيل التي تم اختبار نشاطها الأليلوباثي في الدراسات السابقة، أظهر القمح نشاطًا قويًا ضد مجموعة واسعة من أنواع الحشائش. فيما ركزت العديد من الدراسات السابقة على تعريف المواد الكيميائية الفعالة في القمح المسؤولة عن التأثير الأليلوباثي ضد الحشائش، فإن الدراسة المرجعية الحالية تعرض محموعة من التفاصيل حول المجموعات الكيميائية الأكثر أهمية وتأثيرًا، بما في ذلك البنزوكسازينويد والمركبات الفينولية. بالإضافة إلى ذلك، تم سرد العديد من الطرق لاستغلال قدرة القمح في مكافحة الحشائش ، بما في ذلك ادخال القمح في الدورة المحصولية، أو استخدام مخلفاته كغطاء للتربة ، أو معاملة الحشائش بالمستخلص المائي للقمح. كما تم عرض خلفية عامة حول ظاهرة الأليلوباثي والمواد الأليلوباثية من حيث مفهومها وأهميتها ومجموعاتها الكيميائية وطريقة عملها وتأثيراتها البيئية.

الكلمات المفتاحية: القمح، الأليلوباثي، المواد الأليلوباثية، الفينولات، البنزوكسازينويدات ، مكافحة الحشائش، المستخلص المائي