

Review Article

Phytotoxicity of Natural Molecules Derived from Cereal Crops as a Means to Increase Yield Productivity

Hiwa M. Ahmed ^{1,2}, Ehsan Amiri-Ardekani,^{3,4} and Sayed Ebadi ⁵

¹Sulaimani Polytechnic University, Slemani 46001, Kurdistan Region, Iraq

²Department of Horticulture, University of Raparin, Ranya, Kurdistan Region, Iraq

³Department of Phytopharmaceuticals (Traditional Pharmacy), Faculty of Pharmacy, Shiraz University of Medical Sciences, Shiraz, Iran

⁴Research Center for Traditional Medicine and History of Medicine, Shiraz University of Medical Sciences, Shiraz, Iran

⁵Department of Horticulture, Faculty of Agriculture, Baghlan University, Baghlan 3601, Afghanistan

Correspondence should be addressed to Sayed Ebadi; khalifaebadi@gmail.com

Received 18 February 2022; Accepted 8 May 2022; Published 27 May 2022

Academic Editor: Francesca Degola

Copyright © 2022 Hiwa M. Ahmed et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Phytotoxicity including autotoxicity and allelopathy is the immediate or indirect biochemical impact of one organism on the germination, growth, survival, and reproduction of other organisms or improvement of neighbouring plant species through the arrival of substances into the environment. This biological phenomenon effect might be either growth-enhancing (synergistic) or inhibiting (hostile), contingent upon the chemical substances delivered from donor plants and target species. Allelopathy has been viewed not just as a nature-accommodating way to control unwanted plant species and biocidal products, but, additionally, a potential explanation for causing autotoxicity in yield. The application of chemical agents to reduce weed infestation may have negative consequences on human health as well as the environment. Plants with allelopathy activities derived from secondary metabolites could be an alternative strategy and have an expected function in sustainable weed biocontrol and boost global agricultural production and food security. Thus, protecting biodiversity, ensuring food safety, improving food, and nutrient quality, as well as crop production, are urgently needed as population and consumption are increasing. So, the objective of this study is to present recent advancements on phytotoxicity and allelopathic effect of plant extracts (sorghum, sunflower, rice, and corn), for sustainable food and crop production in agroecosystems.

1. Background

Any immediate or backhanded chemical impact of one plant on the germination, development, or improvement of adjoining plant species through the arrival of substances into nature is called phytotoxicity (allelopathy) [1, 2]. Active substances are released from various parts of plant species into the environment by different paths including (phenolic acids, terpenoids, and alkaloids) [3–9]. Several factors mark their toxicity, for example, flux rate, age, concentration, climatic and environmental conditions, and the metabolic state of the plant [9]. Their quality and amount vary

according to the season, cultivar, age, and plant organ [9, 10]. Allelopathy assumes a significant job in natural as well as managed biological systems, particularly agroecosystems, for example, weed control, food and crop security, and yield refoundation, because of its antagonistic consequences for germination and seedling growth [11]. However, synthetic herbicides could successfully manage weeds, but can also bring about a few impairments to the human wellbeing and environment, and increment herbicide-safe weeds [9, 12]. Allelopathy has been taken into account not solely as a nature-friendly methodology for killing weeds but additionally as a possible explanation for

resulting in autotoxicity in crop output [13]. Thusly, this has urged overall research to limit reliance on manufactured herbicides and to find new other options.

Yield maximization is required to meet human needs, as its populations are growing [6]. Weeds are unintended plants when growing with intended plants which usually compete with other plants for resources such as water, space, nutrients, and light and decrease the quality and quantity of crops [12, 14].

Plants that produce allelopathy properties are known to have a major part in sustainable weed control [9, 15]. Many plant species discharge allelochemicals into nature and have organically dynamic aggravates that stifle the development and improvement of other plants [9, 16]. Crop allelopathy has been reported as an ecofriendly, economical, and sustainable approach that could probably be utilized as a herbicide for weed control [9, 17]. Cereal crops such as sunflower [8, 14, 18, 19], sorghum [14, 18, 20, 21], and rice [22, 23] have been extensively evaluated to display allelopathic influence on other plants (crops and weeds). Corn (*Zea mays* L.) is the third significant food cereal crop that is commonly cultivated all over the world for human, animal feed, and industrial uses [24, 25].

It possesses many allelochemicals and, hence, has phytotoxic potential against itself [24], weeds [21], and other crops [24]. Because of the widely spaced corn rows, weeds are regarded as one of the major restricting factors for corn yield and affecting economic returns [24]. Therefore, the present review aims to present the potential application of allelopathy of grain crops on germination and seedling growth of other plant species as a potential natural herbicide.

2. Allelopathy

Allelopathy as a potential plan for controlling many weeds in agriculture is the subject of much research and was coined by Prof. Hans Molisch in 1937 [5, 8], derived from the Greek word 'allelon' signifying 'one another' and 'pathos' signifying 'hardship' [6, 26]. 'Pathos' likewise signifies 'feeling' or 'sensitive' and accordingly could be utilized to allude to both good (sympathetic) and negative (woeful) connections [6]. Rice [4] characterized allelopathy as the impact of one plant on different plants by means of the arrival of active agents into the climate. However, this is widely passable to indicate the stimulatory (beneficial) or/and inhibitory (detrimental) biochemical interaction between plants containing microbes [6, 27], but many ecologists prefer definitions including only negative effects in allelopathy [6]. Since the emergence of the term allelopathy, a study has been begun in various scopes. The International Allelopathy Society, in 1996, modified the meaning of this term as "Allelopathy alludes to any interaction including chemical compounds delivered by plants, microbes, viruses, and fungi that impact the development and improvement of biological and agricultural systems (except animals), including positive and adverse consequences" [5, 28]. A plant that has potential allelopathic activity is known as the "donor plant" while the plant influenced by allelopathic chemicals from the contributor plant is known as the "acceptor plant" [29].

Active substances with potent activity are potentially useful molecules in the area of pharmacology, agricultural engineering, and others. In the last ages, chemical interaction in the environment is advancing fast. Natural products isolated from medicinal plants and other crops have potential use not only in pharmacology, but in many areas especially as herbicides and pesticides [30, 31]. Active substances delivered from plants, forcing allelopathic impacts, are called allelochemicals or allelochemicals [3, 6, 32]. They are categorised as secondary metabolites and often their functioning in the plant is not known, except a few of them which are known to have primary capacities (for example as intermediates of lignifications) or defend plants against an animal that feeds on plants and microorganisms [26, 33]. Chemicals can be produced by plants either above (leaves, stems, seeds, buds, fruits, pollens, and flowers) or below (roots, rhizomes, and stems) the ground, or both and resulting in allelopathic effects in various plant communities [1, 11, 34–36]. These different plant parts produce various amounts of allelochemicals. The biosynthesis and excretion of these biomolecules are affected by biotic and abiotic factors, following a featured temporal and dynamic pattern [31, 37–39].

Allelochemicals are often water-soluble substances [35], which can be released into the environment by diverse routes (Figure 1) such as root exudation, leaching from aboveground parts such as aerial plant parts, volatilization, and decomposition of the material [4–6, 9, 26, 40, 41]. These chemicals can pass or influence another plant straight by take-up of the influenced plant or in a roundabout way by impacts of the allelochemical on soil microorganisms that are either plant development promoters or that are pathogenic [5].

Phenolic compounds (Figure 2) are the most important and widespread allelochemicals among secondary plant metabolites, with numerous functions including allelopathy function. Other allelochemicals include alkaloids, terpenoids, flavonoids, carbohydrates, amino acids, steroids [11, 26, 33, 42], benzoxazinoids, cyanogenic compounds, cinnamic acid derivatives, and ethylene [6]. Their concentrations in plants vary according to plant parts and types of solvents [43, 44]. These allelochemicals have been extracted from more than 30 families of earthly and oceanic plants that have real or likely phytotoxicity [6]. Chon and Nelson [11] reported that fewer certain allelochemicals have been identified, although allelopathic interaction between plants has been identified for centuries. The effects of allelopathic chemicals released from plants are probably derived from a combination of several allelopathic compounds and may have effects on germination, growth, and development [33]. Laboratory experiments have shown the greater effect of combination solutions of allelochemicals than the same concentrations of single compounds when they are employed independently [33]. Additionally, they exhibited that a combination of some allelochemicals such as polyphenols, carbohydrates, and amino acids can have allelopathic properties, although concentrations of single compounds have much lower inhibitory levels [34]. There are a lot of factors that can affect the production of



FIGURE 1: The routes by which allelochemicals may be released to the environment to inhibit and/or suppress other organisms or be stimulatory to growth-promoting.

allelochemicals in plants such as biotic and abiotic factors, water and nutrient availability, light, pesticide treatment, and disease [33]. The choice of allelopathic plants is a decent and normally utilized methodology for the identification of plants with secondary metabolites [6, 17].

Researchers have suggested the important role of allelopathy in the assurance of supplement elements, soil substance qualities, mycorrhizae, microbial environment, plant variety, invasion, dominance, progression, and the peak of normal vegetation [4, 26].

3. Bioassays as a Means for the Study of Phytotoxicity

Bioassays as a useful tool for the study of phytotoxicity have been effectively used to recognize the biological property of various active agents (allelopathic/allelochemical effect) and synthetic compounds [1]. There are many designs for bioassays that have been proposed to assess interactions of phytochemicals on plants (phytotoxicity) and microorganisms (plant guard and anti-infection effect), microbial mixtures and microorganisms on plants (phytotoxicity/pathogenicity), and organisms on microorganisms (anti-infection action) [5]. Biological activity concerning allelopathic research usually includes seed germination, coleoptile

development tests, entire seedling/plant tests, membrane impacts through the revelation of electrolyte spillage and ethane creation, photosynthetic effect (oxygen growth and chlorophyll creation), and others [5]. Biosynthetic gene clusters may also manage these allelopathic interactions. Late genomic investigations of weedy plants are giving an in-depth overview of the development of unwanted grasses and the systems of yield weed communications and are probably going to majorly affect weed control and plant breeding [45]. Because of the difficulty of the process of separating competitive compounds from allelopathic interactions under field conditions [5], the study of allelopathy based on biological assays have been intensively carried out in the laboratory or controlled conditions and in some case conducted bioassays under controlled conditions are crucial for understanding the phenomena of allelopathy [5, 46].

Various studies deciding on the hereditary systems related to crop-weed interactions have indicated that the phytotoxicity impacts are profoundly intricate. These have been classified into biological and physiological impacts, for example, hindrance of the division of a cell and elongation, antioxidant systems disturbance, rising cell film penetrability, and impacts of allelochemicals of microbes and the prompt ecology [47–50]. The importance of laboratory, growth chamber, and greenhouse bioassays is clear to

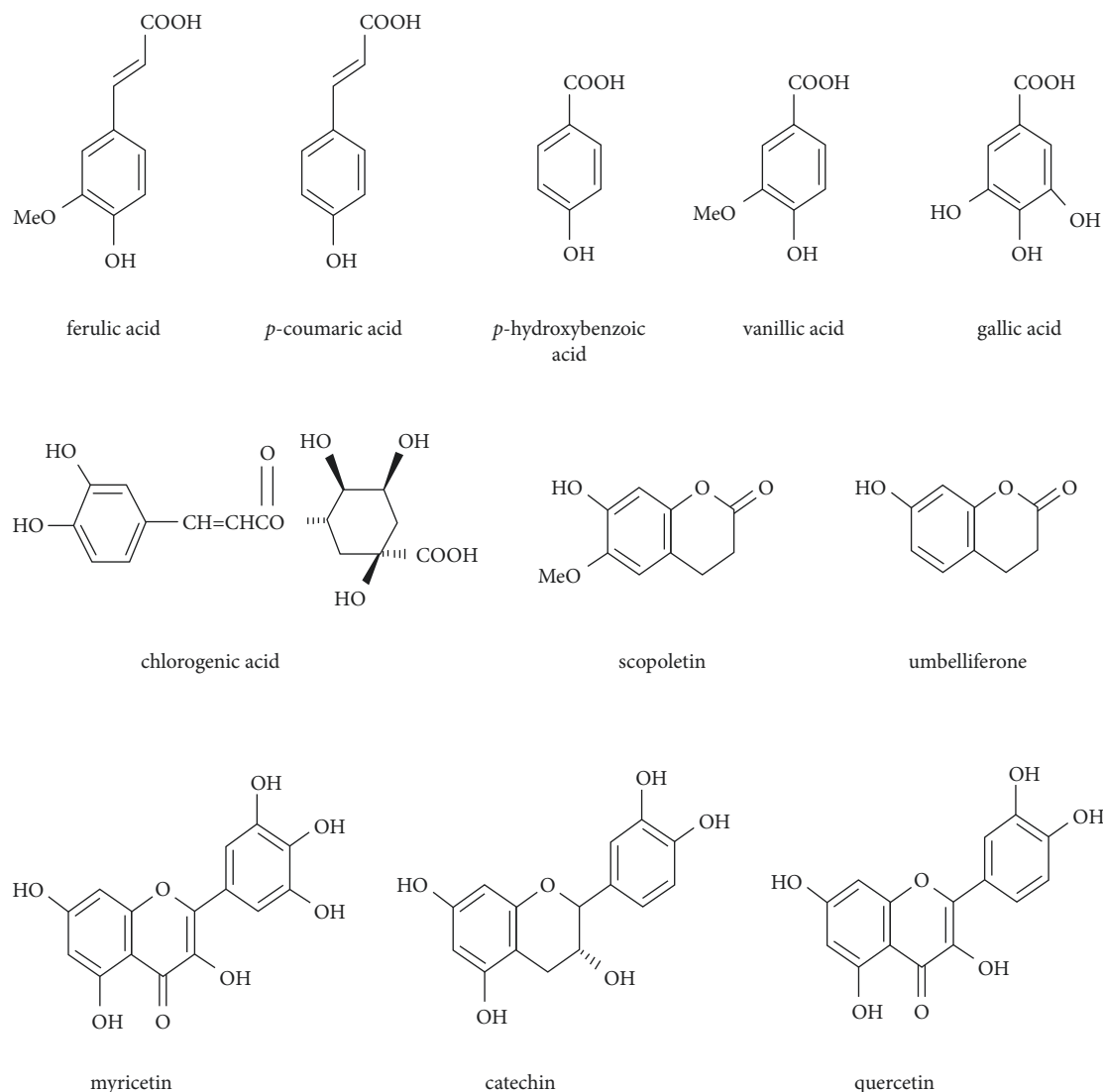


FIGURE 2: Chemical structures of some common compounds leading to allelopathic effects such as (a) ferulic acid; (b) (p)-coumaric acid; (c) (p)-hydroxybenzoic acid; (d) vanillic acid; (e) gallic acid; (f) chlorogenic acid; (g) scopoletin; (h) umbelliferone; (i) myricetin; (j) catechin; and (k) quercetin.

address this allelopathic action in nature [5, 46]. Additionally, for phytotoxicity of secondary metabolites, bioassays are also important during isolation, purification, and identification [46].

Although plant growth bioassays [51], bioassays based on pigment analysis [52], electrolyte leakage as a bioassay [52, 53], isolated systems as bioassay specimens [54], and bioassays to detect inhibition of photosynthesis [55] have been used in plants, the most frequent tests reported in the allelopathy study are perhaps seed germination bioassays. Seed germination is regarded to be the foremost significant stage, particularly beneath pressure conditions, in which some biochemical alterations occur and give the fundamental structure for the succeeding development and improvement [36]. However, the disadvantage of this process is that seed germination is probably not as touchy to the impacts of chemicals released as plant development or other plant forms [5].

Due to the fact that germination is perhaps not the main target, many researchers pay additional attention to the sprouting seedlings since they are the major target of most allelochemicals [5, 56]. The lengths of the radicle, hypocotyl, and coleoptile are frequently measured [5]. Allelochemicals have a number of apparent impacts on plant growth and development comprising seeds darkened and swollen; inhibited or slow germination rate; swelling or necrosis of root tips; decreased radicle (root) and coleoptile (shoot) expansion; discolouration and lack of root hairs; root axis curling; increased number of seminal roots; lowered reproductive capacity; and decreased dry weight accumulation [6]. These morphological effects are probably triggered by a range of specific actions on the receiver plants at the cellular or molecular level [6]. Kamal [57] illustrated that leaves contain higher amounts of allelochemicals than roots, but this can be reversible in some plants; occasionally stems are the primary principal source of toxicity, and leaves are often

major sources of allelochemicals. Thus, the natural path could be employed to improve food production and lessen human and natural health effects, especially by diminishing our reliance on pesticides and manures [58].

4. Allelopathy and Weed Management

Future farming exploration should progressively incorporate natural, physiological, and anatomic strategies, to comprehend horticultural yields in situ and their collaboration with the environment just as living beings affecting their long haul wellbeing and efficiency (agrarian ecogonomics) [59]. Undesirable weeds that have grown close to crop types are known for fast adaptation and invasion, which can bring about a tremendous decrease in yearly plant yield around the world [45, 60, 61]. Currently, there are at least 512 herbicide-resistant weed species in the world [62].

A major problem of modern agriculture which causes a ten percent drop in agricultural output globally is weeds [11, 63]. Weeds are the attacker, competitive, upsetting, and unwanted components growing with intended plants and they pose multidimensional problems for plants in every cropping system, more importantly, a reduction in crop yields as a result of interference (competition) [12, 14]. Weeds react with agricultural crops on the different roads such as chemical reactions, rivalry for purses, and hereditary host-parasite interaction. These relationships occur during an environmental period, but they can result in a variety of alterations on a developmental timeline [45]. Nevertheless, the molecular mechanisms of this fast adaptation for the development of weedy plants in crop fields are yet unknown. Reference plant genomes have provided new insights into the developmental and physiological processes that plant species use to respond to their environments [64]. Allelopathy phenomenon has appeared to play an imperative part in diverse disciplines of agriculture and biology fields that might be used to control pests [8]. It is gaining popularity for weed management due to the concerns rising from chemical usage [3, 34, 65]. Allelochemicals are currently known to be future chemicals as a potential strategy for pest management that has no negative environmental consequences [65]. Sustainable agriculture is required to maintain the natural resources and allelopathy as an important tool in agriculture may serve as a fundamental for long-term agriculture in the future [8]. As a result, in order to be sustainable, future weed control approaches must limit the usage of herbicides and instead employ allelopathic methods and other weed management approaches [8, 66]. Present-day agribusiness is focused on the production and depends mostly on engineered inputs to address undesirable grasses [14, 67]. Irregular utilization of herbicides to combat unwanted herbs in recent decades has led to environmental and ecological issues to the planet and its inhabitants [8, 14] as follows:

- (1) Weeds are becoming more resistant to several essential herbicides, such as dinitroanilines and S-triazines, and herbicide-resistant crops, in contrast to pest-resistant crops, will cause farmers to rely more and more on herbicides, hence increasing herbicide use in farming.

- (2) Weed population shifts in those species that are associated with the crops infested, for example, *Avena fatua* in oat and sorghum and *Oryza fatua* in rice, and this has resulted in minor weeds becoming more dominant.
- (3) Increased environmental pollution and health risks especially from the pollution of surface and groundwater, for both human and cattle utilization; for example, the groundwater of the USA comprises a considerable amount of widely used herbicides alachlor and atrazine.
- (4) Potential exposure of future generations to toxic residues of herbicides due to its effects on the environment.

As a result of these reasons, growing concerns have been raised regarding the usage of herbicides to combat undesirable grasses [8, 14]. The present aim is to reduce reliance on traditional techniques and synthetic pesticides and to develop alternative weed management tactics [1, 14, 68]. Therefore, FAO Expert Consultation Group on 'Weed Ecology and Management' has recommended alternative strategies to remove or minimise the usage of herbicides to control weeds [8]. Weeds were managed using mechanical and cultural means before the invention of herbicides. Current knowledge of plant morphology, physiology, natural product chemistry, and inter- and intraplant relationships has demonstrated that allelochemicals, trap crops, and smothering crops probably could be used to control weed. Allelopathy has the potential to aid in weed management by inhibiting unwanted plant seed sprouting and seedling development [8].

A number of allelopathic methodologies have been suggested for potential weed repression: firstly, selection of cover crop residues (weeds that cover crops) and developing their varieties to suffocate key weeds within a specific region. Secondly, the use of alive rotating crops or their leftovers as mulches that inhibit the development of encompassing unbeneficial herbs. Finally, identifying allelochemicals with herbicidal action in plants or microorganisms [11, 69]. Hoagland et al. [5] argued that the effects of phenolic allelochemicals probably at very low concentrations are stimulatory, while in larger doses restrain functions within the accepting species. It ought to be referenced that allelochemicals must fulfil some conditions before they may be registered as herbicides: demonstrated phytotoxic activities somewhere in the range of 10^{-5} and 10^{-7} M, depicted synthetic structure, plants with a known method of action, known time of habitation in soil, conceivable poisonous on human wellbeing, and suitability of creation at the manufacturing level [70, 71].

5. The Importance of Crops and Their Potential Allelopathic Effects

Plant foods are one of humanity's most important needs, and people and plants are presently harmoniously intertwined due to their common dependence on them for survival. Plants provide 80 percent of human nutrition; thus,

seven billion people cannot be fed without agriculture. On the other hand, people guarantee the endurance of a portion of our significant crops, given that plant breeding and domestication have disposed their capacity to survive on their own [72]. There are approximately 420,000 plant species living on the planet [73, 74], in which probably around 2,500 species have been domesticated for cultivation [75]. Around 100 species account for 90 percent of the calories consumed by humans; other types function as springs of fundamental supplements, for example, proteins, nutrients, and minerals, and as medicinal prescriptions [72, 73]. Thus, taking the best strategy and alternative methods to increase productivity is essential to overcome the enemy of crops.

Chon and Nelson [11] and Jabran and Farooq [76] demonstrated that some species including crops, weeds, agroforestry trees, and fruit trees have been discovered to have allelopathic activity. Only crop plants, however, attracted the greatest attention for the research of probable allelopathy in nursery bioassays and field circumstances as well [76]. Various investigations have demonstrated that there are huge contrasts between crop cultivars in their capacity to stifle weeds and these distinctions have been clarified to some degree by methods for variable ability to emit synthetic substances influencing weed development, i.e., allelopathy [77]. Crops have been proposed to show allelopathic effects (Table 1, Figure 3), on other plants such as corn (*Z. mays* L.), sunflower (*H. annuus*), barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), beet (*Beta vulgaris* L.), oats (*Avena sativa* L.), rye (*Secale cereal*), and lupin (*Lupinus lutens* L.). Its extracts possess different allelopathic compounds as potential use of herbicides, which play a critical part in weed management [6, 65, 76], and have developed structural models for the manufacture of the herbicides [65], with the synchronous decrease of herbicide application as an appealing view for sustainable farming [84]. The foremost commonly detailed crops and other species with allelopathy activity incurred weeds, and treated crops are listed in Table 2. The allelopathic effects of corn parts (root and shoot), with two solvent extracts (water and ethanol), were studied against some indicator species (corn, Johnson grass, wheat, sunflower, and canary grass). Results showed that active substances in corn parts greatly prevented the growth of the tested species. This is probably due to the allelochemicals present in plant part tests that contribute to this effect [1].

5.1. Sorghum. Sorghum (*Sorghum arundinaceum* (Desv.) Stapf) is an annual crop from the family Poaceae [85]. Sorghum may be used for a variety of purposes, including human nutrition (Africa, China, and India) and animal feed grain (America and Australia). Sorghum has recently gained popularity as a biofuel crop of the future due to its diverse use and adaptability to alterations in the state of the agricultural climate. For instance, in the United States, more than 30 percent of grain sorghum is currently utilized in the production of fuel ethanol, which results in a large amount of dried distiller grains with solubles as a byproduct. Consequently, the need for additional value-added vents for

sorghum has become critical to maintaining the sorghum business's financial viability [86]. Sorghum has additionally become another age bioenergy crop as a result of its wide flexibility to different agricultural climatic statuses and its capacity to limit inputs, for example, water as well as nitrogen, which might be essential to sorghum benefits as a bioenergy crop [87].

Sorghum is one of the foremost broadly studied plants with regard to its allelopathic potential [14]. Sorghum water extract's effects on weed species (sprouting response and plantlet growth) were evaluated in various bioassays. Cheema and Khaliq [20] investigated the phytotoxicity impact of sorghum to combat undesirable herbs in watered wheat and the effect of concentration and frequency of sorgaab application in the semiarid region of Punjab. They found that the use of sorgaab spray lowered the dry weight of the weed up to 49% and improved wheat crop by 21%. Sorghum stalk incorporation into the soil at 2, 4, and 6 Mg ha⁻¹ decreased unwanted plants by 42, 48, and 56%, correspondingly. There was not much difference between one, two, or three sorgaab sprays at 1 : 10 and three sprays at 1 : 20 ratio at 90 days.

Ayeni and Kayode [21] studied the allelopathic activity of powdered extracts of sorghum stem residues on the sprouting and development of *Euphorbia heterophylla* L. They found that sorghum extracts caused a reduction in the sprouting of *E. heterophylla* weed and the level of the reduction improved with increasing concentration. Similarly, Cheema et al. [18] conceded a study of the feasibility of allelopathic extracts of mature sorghum in field trials as a natural strategy to control weeds for the wheat crop. A concentration of 100, 50% water extracts, was sprayed 30 days after planting the wheat crop while control plots received no spray. They revealed that spraying sorghum 100% water extracts reduced weed up to 53% and it suppressed individual weed species as *Chenopodium album* 38%, *Fumaria parviflora* by 40%, *Coronopus didymus* by 62%, and *Rumex dentatus* 74%. The use of 100% sorghum extract enhanced wheat production by 14%. Sorgaab's allelopathic action was studied in *Eucalyptus camaldulensis* Dehnh, *Dalbergia sissoo* Roxb., *Acacia nilotica* L. Willd. Ex Delile, *Populus deltoides* W. Bartram ex H. Marshall, and *Nicotiana tabacum* L. The results revealed that repeated applications of sorgaab reduced dry biomass by 62 percent [88].

Recent greenhouse research found that combining 150 g/ mL sorgoleone with 7.5 mg/mL tartary buckwheat (*Fagopyrum tataricum* Gaertn.) showed more prominent development hindrance of broadleaf weeds than grass weeds instead of individual concentrates specifically [89]. In particular, the blend of these two molecules repressed the development of *Aeschynomene indica* L., *Rumex japonicus* Houtt., and *Galium spurium* L., by 90%, 96%, and 100%, individually, while the use of sorgoleone alone prompted the development concealment of these weeds species by 81%, 83%, and 75%, separately because of the mechanism of action of sorgoleone is directed towards the photosynthetic electron transport chain [90, 91]. From a structural point of view, sorgoleone is like plastoquinone (a lipid

TABLE 1: Potential natural herbicides and chemicals of some important crops as herbicides.

Plants	Scientific name	Active compounds	References
Rice	<i>Oryza sativa L.</i>	Phenolic acids, momilactone B, momilactone A, 3-hydroxybenzoic acid, 3-hydroxy-4-methoxybenzoic acid, 4-hydroxybenzoic acid, p-coumaric acid, caffeic acid, tetradecanoic acid, valeric acid, stearic acid, 2-methyl-1,4-benzenediol, 4-hydroxybenzaldehyde	[6, 78–80]
Sorghum spp.	<i>Sorghum bicolor L.</i>	Sorgoleone, strigol	[6, 65]
Corn	<i>Zea mays</i>	Corn gluten meal (MGM), maize gluten	[53, 65]
Sunflower	<i>Helianthus annuus</i>	Coumarins, flavonoids, heliannuol, lignans, sesquiterpenes, triterpenes, heliannuol M and A, heliopyllides K and L, gallic acid, helieudesmanolide B, catechin, α -pinene, β -pinene, benzoic acid, leptocarpin, 3,4-dihydroxybenzoic, camphor, 1,8-cineole	[65, 81, 82]
Wheat	<i>Triticum aestivum L.</i>	Hydroxamic acids, DIBOA	[6, 65]
Oat	<i>Avena sativa L.</i>	Phenolic acids and scopoletin	[6, 83]
Black mustard	<i>Brassica nigra L.</i>	Allyl isothiocyanate	[6, 83]
Cereals	-	Hydroxamic acids, DIMBOA, TRIBOA	[6, 83]
Buckwheat	<i>Fagopyrium esculentum L.</i>	Fatty acids	[6, 83]

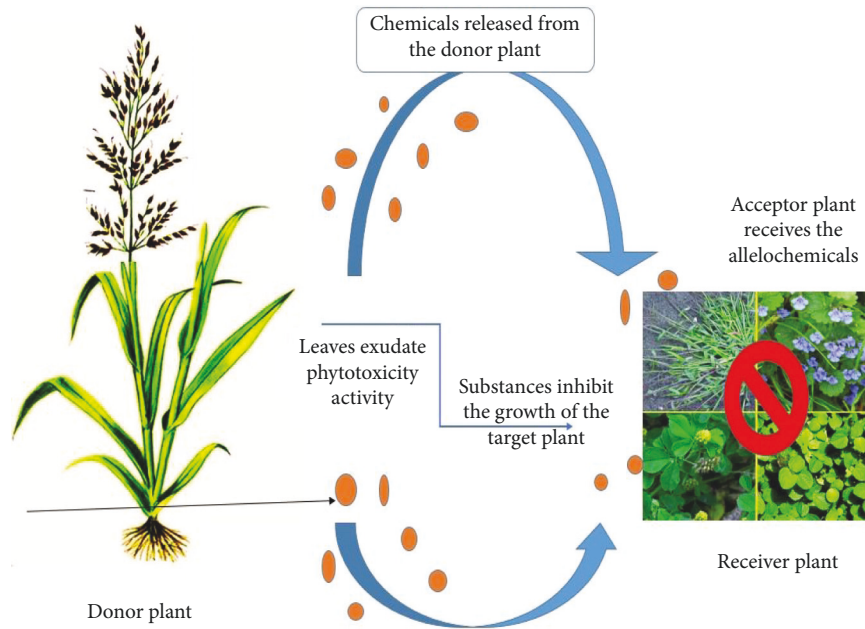


FIGURE 3: Active substances which hinder the growth and development of the target species are released into the environment by plant components under or above grounds.

TABLE 2: The most frequently detailed allelopathic crops that targeted undesirable weeds.

Allelopathic plants	Target weed species	Cultivated crops
<i>Hordeum vulgare</i>	<i>Phalaris minor</i>	<i>Lycopersicon esculentum</i>
<i>Brassica</i> (accessions)	<i>Amaranthus</i> spp.	<i>Brassicas</i> pp.
<i>Echinochloa colonum</i>	<i>Chenopodium album</i>	<i>Helianthus annuus</i>
<i>Festuca arundinacea</i>	<i>Cyperus</i> spp.	<i>Hordeum vulgare</i>
<i>Cajanus cajan</i>	<i>Avena ludoviciana</i>	<i>Glycine max</i>
<i>Helianthus annuus</i>	<i>Echinochloa colona</i>	<i>Lactuca sativa</i>
<i>Oryza sativa</i> and accessions	<i>Trianthema</i>	Orchards
<i>Lolium</i> spp.	<i>Portulaca oleracea</i>	<i>Medicago sativa</i>
<i>Secale cereale</i>	<i>Portulacastrum</i>	<i>Oryza sativa</i> (most frequent)
<i>Sorghum bicolor</i>	Unidentified weeds	Potato
<i>Sorghum halepense</i>		<i>Triticum aestivum</i>
<i>Sorghum hybrids</i>		<i>Vitis vinifera</i>
<i>Sorghum sudanense</i>		<i>Zea mays</i>

benzoquinone), bringing about a rivalry with the typical electron acceptor at the plastoquinone binding site on the D1 PSII protein, which can prevent plastoquinone A reoxidation by plastoquinone B [92, 93]. This mechanism is similar to that of atrazine and sorgoleone is, in this manner, a serious inhibitor that contends with atrazine for the plastoquinone-restricting domain [94]. In research bioassays, watery concentrates derived from above and underground of some sorghum crossbred were found to suppress soybean radicle improvement [95].

5.2. Sunflower. Sunflower (*Helianthus annuus* L.) is one of the world's most important oilseed crops. Sunflower seeds can be ground into flour, used to decorate a variety of recipes, or eaten raw. It is an appropriate choice for animal feed due to its high nutritional value [96]. Sunflower is another crop plant being described to have a potent allelopathic property [14, 97] and also exhibits autotoxicity [8]. Nikneshana et al. [19] evaluated the allelopathic activity of sunflower on several crops and associated weeds. They concluded that their results show inhibitory effects of sunflower against some harmful plants such as *Hordeum spontaneum* and *Lolium rigidum* in wheat and *Amaranthus retroflexus* in safflower. In the laboratory, the phytotoxic effects of fresh and dried water extracts of sunflower root, shoot, and leaves on wheat and maize sprouting and plantlet growth were investigated. Results showed (15.21%) germination inhibited, reduced radical development (21.66%), plumule growth (28.44%), and dropped plantlets dry biomass (31.05%) in wheat. In the case of maize, a similar impact was seen. The dry extract was more effective phytotoxic than fresh, and the leaf of sunflower was more inhibitory than root and shoot extracts effects [97]. Furthermore, Cheema et al. [18] studied the feasibility of allelopathic extracts of mature sunflower in field trials as a natural strategy to control weeds for the wheat crop. A concentration of 100, 50% water extracts, was sprayed 30 days after planting the wheat crop while control plots received no spray. They revealed that spraying sunflower 100% water extracts reduced weed up to 53% and it suppressed individual weed species such as *Chenopodium album* 26%, *Fumaria parviflora* by 33%, *Coronopus didymus* by 42%, and *Rumex dentatus* 73%. The use of sunflower extract enhanced wheat grain production by 7%. Sunflower is another cereal crop despite having inhibition effects on other plants; it also has autotoxicity. Nikneshana et al. [98] evaluated the allelopathic activity of sunflower on several crops and associated weeds. They concluded that their results show inhibitory effects of sunflower against some harmful herbs such as wild barley (*Hordeum spontaneum*) and ryegrass (*Lolium rigidum*) in wheat and redroot pigweed (*Amaranthus retroflexus*) in safflower. Among sunflower cultivars, Suncross-42 was discovered generally to have inhibitory action against germination and dry weight amassing of weeds, while Gulshan 98 was only active against weed root development [99]. Pannacci et al. [100] assessed the allelopathic potential of sunflower cultivars to combat *Sinapis alba* L., *Lolium multiflorum* Lam., wheat. Sunflower cultivars were extremely shown to prevent weed with little impact on wheat.

5.3. Rice. Rice is also the most stable food and has antiweed and anticrop properties [13]. Some rice assortments discharge chemicals which may influence significant undesirable plants, microorganisms, and pathogenic around the cultivated crops and soil attributes. These have been distinguished in rice root secreted and decompositions, which interact with ecological conditions as an environmentally beneficial agroproduction system [101]. Several natural molecules have been recognized as potential rice inhibitory chemicals [101, 102].

Albeit various investigations have been attempted, allelopathy among rice and barnyard grass is the most profoundly inspected in light of the fact that both the yield and weed genomes are promptly accessible. The mechanism of allelopathic interactions between a typical crop (rice) and weed (barnyard grass) has been determined. Rice reacts to barnyard grass stress by expanding the creation of potential allelopathic agents such as momilactones, phenolic acids, flavones, and their aglycones, hence increasing allelopathic action against target weeds in the rice-barnyard grass co-culture framework [103, 104]. Nine rice varieties' root exudates were tested against sunflower broomrape, wheat, rice, clover broomrape, and lettuce seeds. All rice species impeded the growth of wheat seedlings. Root exudates from two rice cultivars (I-Kung-Pao and Yliangyou 3218) aided lettuce germination. Autotoxicity was higher in two cultivars (Ganxin 203 and I-Kung-Pao) than in others. The greatest germination rates of clover broomrape and sunflower broomrape were induced by cultivars (I-Kung-Pao, Yongyou 13, Yongyou 15 and Zhongzao 22) [13]. The bioassay was carried out to investigate the biological activity of various portions of rice crops, as well as the hereditary and phenotypic characters, on *Echinochloa crus-galli* P. Beauv. var. *oryzicola* Ohwi. Duchungjong on *E. crus-galli* had a higher inhibitory effect (77.7%) than the inhibition by other varieties. The Damaging strain has a very high rate of germination inhibition produced by a leaves-plus-straw combination (95.9%). Daegudo had the greatest proportion of suppression (93.2%) by husk remains [22]. Kolahi et al. [23] evaluated the potential chemical activity of hull extracts of 13 rice cultivars, on seed sprouting and plantlet development of wild oat (*A. ludoviciana*), which had a significant reduction of wild oat. They came to the conclusion that rice husk extracts might be employed as a natural herbicide source. The allelopathic effect of rice (root, stem, leaf, and whole) and various rice extract concentrations (0%, 25%, 50%, and 100%) on maize germination and seedling development was investigated. The results showed that there was a considerable influence on corn germination percentage, radicle, and coleoptile weight and length [25].

The allelopathic potential of 44 rice cultivars was evaluated in laboratory, greenhouse, and field trials. Rice cultivars displayed remarkable variation in their ability to prevent barnyard grass growth and development. In the laboratory, Gin shun rice cultivar extracts showed the best action on the seedling growth and weight by 61%, while Kasarwala mundara cultivar extracts displayed the best action on seed germination, and speed by 23%, 46% respectively. In a greenhouse trial, the Philippine 2 cultivar showed the highest percentage of inhibition on

seedling growth (57%), length (74%), and dry weight (74%). In the field trial, the Juma 10 cultivar showed a significant activity impact by decreasing weed tiller number, leaf area, leaf, stem, and dry weight (80%, 49%, 61%, 74%, and 68%) in any order. These outcomes propose that there are contrasts in the plant species for the chemical hindrance of barnyard grass [105]. Rice varieties' allelopathic capacity will most certainly have a significant influence on paddy weed control if combined with cultural management methods and the administration of modest dosages of herbicides. As a result, if allelopathic rice is produced using integrated cultural management methods, it is possible to minimise pesticide use in paddies [106].

5.4. Corn. *Zea mays* L. also known as maize or corn is one of the most agriculturally known commercial plants [107], as well as the third most cultivated food crop after wheat and rice [108], belonging to the grass of the monocot family Gramineae (Poaceae) [109]. It is a member of cereal crops such as barley (*Hordeum vulgare*), rice (*Oryza sativa*), wheat (*Triticum* spp.), and sorghum (*Sorghum bicolor*) [109, 110]. The origin of maize is said to be from Southern Mexico. However, modern maize was derived from a wild ancestor called Teosinte (*Euchlaena*), but it has been suggested that modern maize was derived from a Mesoamerican maize variety called *Chapalote* [111]. It was domesticated by native peoples in Mesoamerica roughly 8000 years ago. Currently, maize planting areas broaden to the Americas, Europe, Africa, South Asia, and the Far East [111] and are now cultivated globally [112].

It is not only a vital supply of oil for cooking, fuel, livestock, and poultry feed [113], but different goods like plastics, dye, shampoo, tiles, and wrapping materials are also formed from maize. Moreover, corn is one of the built-up demonstrated life forms for hereditary qualities inquire about; presently, it is one of the driving models for plant utilitarian genomics [109]. Corn plant has been utilized as a medicinal plant in treating various ailments due to being rich in phytochemicals [114, 115]. It is right now farmed on around 100 million hectares in 125 developing nations, and it is one of the top three crops in 75 of those nations [116]. Although approximately 78% of the world's corn production is used to feed livestock, especially in industrialised countries, human consumption is steadily expanding in many emerging and developed nations, including Africa and Latin America [116]. Corn is used in the European Union (EU) as both a feed and a raw material for industrial goods. As a result, breeders in the US and the EU concentrate on agronomic features for use in the animal feed sector, as well as many industrial qualities such as starch, dextrose, glucose, fuel alcohol, and fructose corn syrup [117].

Corn may be yellow, orange-yellow, white, purple, mottled, red, sun red, or brown [116]. There are a number of corn types that have been used for food, fodder, and fuel purposes which are categorised according to the component, kernel features, and endosperm as follows [111, 116].

Flour corn *Zea mays* var. *amylacea* is mostly grown in the Andean area. Its endosperm is primarily made up of downy starch, making it simple to crush and turn into meals.

Popcorn *Zea mays* var. *evarta*: kernels have a larger percentage of firm endosperm than any other maize kernel.

It is cultivated on a limited level than other varieties, yet popped kernels are enjoyed as a snack item all throughout the world.

Dent corn *Zea mays* var. *indentata* is the most extensively farmed form for grain and silage animal feed, and it is the dominating kind farmed in the US. It is distinguished by solid endosperm on the edges and base of the kernel, with downy starch filling the remainder. It requires particular processing to be suitable for human consumption.

Flint corn *Zea mays* var. *indurata*: kernels are distinguished by a significant proportion of solid endosperm around a tiny downy center. It is cultivated mostly for food in Europe and Latin America.

Waxy corn *Zea mays* var. *Certain*: in comparison to the typical 70 percent amylopectin and 30 percent amylose starch composition, kernels contain totally amylopectin and no amylose starch. It is recommended in East Asia to utilize waxy corn for food and some industrial purposes; it provides starch comparable to tapioca.

Sweet corn *Zea mays* var. *Saccharata* and *Zea mays* var. *rugosa* are cultivated for its sweet corn and are frequently cooked and consumed as a vegetable. Ears are collected approximately 18–20 days after pollination when the kernel contains roughly 70% moisture. Because of one or more recessive mutations in the genes that prevent the sugar conversion to starch within the endosperm, sweet corn growth is significantly higher in sugar and lower in starch.

Corn may grow in a variety of agroecological conditions, although it prefers a warm temperature. At least the average daily temperature for adequate growth of corn is 20 °C with warm daytime (25–30 °C) and chilly nights. Temperatures above 40°C and below 8°C lead to severe detrimental conditions [112]. High temperature affects adversely kernel development and bulk and the accumulation of endosperm zein protein. Corn producers and consumers are expected to account for a major portion of the rising demand for cereals overall [113]. Therefore, to increase corn production, substantial changes are required in agronomic practices [113].

Past examinations demonstrated that corn has chemical agents that influence different plant species and eventually bring about a decrease in seed sprouting and production. Cyclic hydroxamic (Hx) acids such as 2,4-dihydroxy-7-methoxy-2H-1, 4-benzoxazin-3-one (DIMBOA), and 2, 4-dihydroxy-3H-1, 4-benzoxazin-3-one (DIBOA) are natural compounds, found in cereals, including such crops (corn and wheat). These are produced by corn plants, under stress conditions during seedlings and play a major role against pests and diseases, possessing allelopathy activity [76, 118, 119]. Benzoxazinoids (Bx) are natural phytotoxins that work as synthetic resistance mixes in a few species and the importance of concentrations of exudate of Bx for plant–plant interactions is as yet a disputable inquiry [84].

Neal et al. [119] found that DIMBOA is the main benzoxazinoids compound in corn root exudates in chromatographic analyses (Table 3) and other crops such as wheat, rye, and some dicotyledons [122].

Kato-Noguchi et al. [120] isolated three allelopathic agents (Figure 4) from corn germination at the early growth stage (seedling) by using acetone extract, which were 5-

TABLE 3: Allelochemicals reported in the corn crop.

Allelochemicals	References
DIMBOA; DIBOA	[76]
Benzoxazolinone; Cl-MBOA; MBOA; DIBOA	[120]
3, 7, 11, 15-Tetramethyl-2-hexadecen-1-ol (phytol); nonanal; (Z)-3-hexenol; neophytadiene; pentadecanal, (Z)-3-hexenyl acetate	[76, 121]

chloro-6-methoxy-2-benzoxazolinone (Cl-MBOA) and 6-methoxy-2-benzoxazolinone (MBOA), 2, 4-dihydroxy-3H-1, 4-benzoxazin-3-one (DIBOA). The same author later [120] evaluated the effects of new (Cl-MBOA) by comparison with its analogues MBOA and BOA on seedlings of some dicots and monocots plants. The author found the inhibitory effect of these allelochemicals on seed sprouting and the development of roots and shoots of crabgrass, cockscomb, lettuce, cress, timothy, and ryegrass. Cl-MBOA was more inhibitor to them followed by MBOA and BOA, respectively. They also concluded that corn germination possesses at least three allelochemicals which may have an impact on the development and germination of other plants [120].

The allelopathy effects of two corn cultivars (301 and 704) and some crops tested on sprouting and development of wheat plantlet. Wheat root number and coleoptile length were reduced as a result of the study's findings [123]. Likewise, aqueous extracts of corn from (roots, stems, and leaves) were evaluated against germination of wild barley (*Hordeum spontaneum*) and found a significant reduction in the shoot at different concentrations. Corn extracts reduced the radicle length of wild barley seedlings (16–47%) as well as wild barley dry weight [35]. Ayeni and Kayode [21] studied the allelopathic properties of aqueous extracts of maize inflorescence residues on the sprouting and development of *Euphorbia heterophylla* L. The results showed that extracts from maize inflorescence caused a considerable reduction in the germination of *E. heterophylla* weed and the proportion of the reduction improved with increasing concentration of the extracts and especially inhibition level seems to be more evident on the coefficient of velocity (COV) [The speed of germination known as COV], number of leaves harvested, and relative growth rates (RGR). Another experiment was performed to study the biological activity of corn water extracts and root exudates against corn and peanut (*Arachis hypogaea*). Results showed the significant inhibitory effects of corn aqueous extracts (shoot and root) on seed germination of both corn and peanut. The shoot extracts were more inhibited than water extracts of root, but its influence on seedling development was the opposite [24].

Regarding germination, when compared to the control, aqueous extracts of the corn stalk and root completely suppressed seed germination of *Phalaris minor* and *Sorghum halepense*. Aqueous extracts of corn shoot inhibited seed sprouting in corn species, with inhibition of 82.2%, followed by sunflower (76.6%) as compared to control. The greatest biological property of corn root extracts was discovered against sunflower and little seed canary grass (100%) on sprouting in comparison to the control. Regarding seedling growth, aqueous extracts of corn shoot and root suppressed seedling growth of all tested species except corn root and

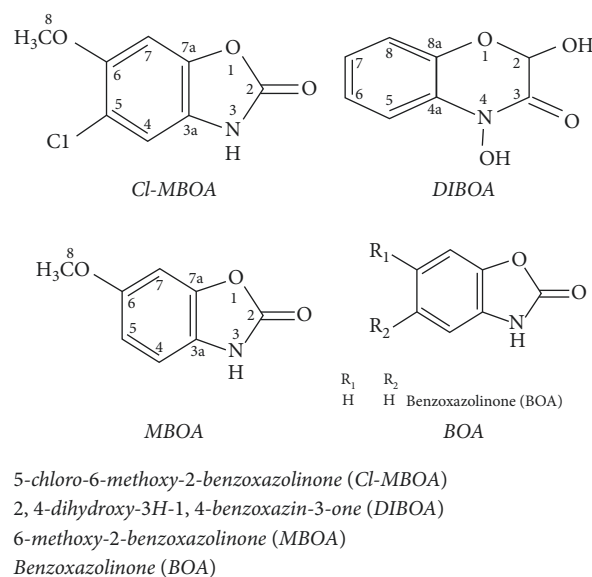


FIGURE 4: Chemical structure of some reported allelochemicals in corn. (a) 5-Chloro-6-methoxy-2-benzoxazolinone (Cl-MBOA), (b) 2, 4-dihydroxy-3H-1, 4-benzoxazin-3-one (DIBOA), (c) 6-methoxy-2-benzoxazolinone (MBOA), and (d) benzoxazolinone (BOA).

shoot length of little seed canary grass, Johnson grass, and sunflower, which was remarkably influenced by the administration of an aqueous extract of corn shoot. Concerning fresh weight, sunflower root is influenced fundamentally by utilization of shoot extracts followed by wheat, and corn individually contrasted with control and in examination with different plants. In addition, a watery concentrate of corn root likewise apparently influenced root new weight of both sunflower and wheat [1]. The study found that corn has even autotoxicity on itself despite having inhibition effects on other plants, and water extracts of corn root and shoot had a significant impact on seed germination, radicle and shoot elongation, and fresh weight of all plant species at different levels [1]. Phytotoxicity of ZnO nanoparticles (ZnO NPs) on sprouting and root length of corn and cucumber were studied. ZnO NPs had no effect on the germination of the targets plant but could ($1,000 \text{ mg L}^{-1}$) decrease the length of corn and cucumber roots by 17% and 51%, correspondingly [124].

6. Conclusions

It can be concluded that the response of target plants to biocidal allelochemicals by receptors could be a better pathway to overcome undesired plants and improve crop yields. Allelochemicals are typically classified as secondary

molecules which are metabolically active in plants and microorganisms; its accumulations vary according to the stage of growth (time and season) and have both positive (stimulatory) effects and negative (inhibitory) effects on plant tests and exhibit significant herbicidal activities in seed germination and growth, by exuding chemicals. This observed suppression could be attributed to the allelochemical effects that are present in different plant parts and various quantities, which lead to a reduction not only in seed germination, even the yield is affected by the length of root and shoot (radicle and hypocotyl) which are two important parameters of seedling growth as well.

However, the required concentration of allelochemicals for seed germination to be inhibited or suppressed is probably higher than it to hinder seedling growth as a whole. Seeds in higher concentrations probably have a lower germination rate and need more time to germinate so the procedure of extracts is another factor to determine the effects. It is necessary to study phytochemicals and the relative abundance of allelochemicals on the plant species to exert an inhibitory effect. It can be seen that the extracts from plant parts or its derived natural molecules have considerable potential to stop or suppress germination and seedling development of various weeds and plants that could be potentially used as natural herbicides to control weeds, which is ecofriendly rather than chemical herbicides although target plant species have different responses to the phytotoxicity effects.

The mechanism of this phenomenon also should be elucidated by isolating allelochemicals and determining the chemicals and their toxicity in inhibiting or suppressing sprouting and plantlet growth of many undesirable weeds using different solvents and HPLC, to verify this influence under different conditions. More importantly, genetically modifying corn and other crops to produce potent allelopathy could be another possible strategy to suppress or resist weeds and other harmful plants instead of using chemical herbicides that induce increasing the crop yield. A greater discovery of this study is that farmers may soon employ natural herbicides to prevent the negative consequences of employing chemical substances and provide economic benefits.

Data Availability

All the data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

- [1] H. M. Ahmed, "Phytochemical screening, total phenolic content and phytotoxic activity of corn (*Zea mays*) extracts against some indicator species," *Natural Product Research*, vol. 32, no. 6, pp. 714–718, 2018.
- [2] J. K. Ooka and D. K. Owens, "Allelopathy in tropical and subtropical species," *Phytochemistry Reviews*, vol. 17, no. 6, pp. 1225–1237, 2018.

- [3] A. R. Putnam, "Allelochemicals from plants as herbicides," *Weed Technology*, vol. 2, no. 4, pp. 510–518, 1988.
- [4] E. L. Rice, *Allelopathy*, 2nd edn, Academic Press, New York, NY, USA, 1984.
- [5] R. E. Hoagland, R. D. Williams, F. A. Macías, J. C. G. Galindo, J. M. G. Molinillo, and H. G. Cutler, *Bioassays Useful Tools for the Study of Allelopathy. Allelopathy: Chemistry and Mode of Action of Allelochemicals*, CRC Press, Boca Raton, FL, USA, 2004.
- [6] P. Bhadoria, "Allelopathy: a natural way towards weed management," *American Journal of Experimental Agriculture*, vol. 1, no. 1, pp. 7–20, 2010.
- [7] S. Hassannejad, S. Porheidar-Ghafarbi, and R. Lofti, "Assessment of seed to seed allelopathic potential of corn (*Zea mays* L.) on seed and seedling growth of some volunteer species," *International Journal of Biosciences*, vol. 3, no. 1, pp. 121–127, 2013.
- [8] S. S. Narwal and R. Haouala, "Role of allelopathy in weed management for sustainable agriculture," in *Allelopathy*, pp. 217–249, Springer, Berlin, Heidelberg, 2013.
- [9] O. J. Won, M. R. Uddin, K. W. Park, J. Y. Pyon, and S. U. Park, "Phenolic compounds in sorghum leaf extracts and their effects on weed control," *Allelopathy Journal*, vol. 31, no. 1, Article ID 147, 2013.
- [10] V. Cambier, T. Hance, and E. de Hoffmann, "Variation of DIMBOA and related compounds content in relation to the age and plant organ in maize," *Phytochemistry*, vol. 53, no. 2, pp. 223–229, 2000.
- [11] S.-U. Chon and C. Jerry Nelson, "Allelopathic dynamics in resource plants," in *Allelopathy*, pp. 81–110, Springer, Berlin, Heidelberg, 2013.
- [12] T. D. Khanh, L. H. Linh, T. H. Linh et al., "Integration of allelopathy to control weeds in rice," *Herbicide-current Research and Case Studies in Use*, pp. 75–99, Intech Publisher, New York, USA, 2013.
- [13] Y. Ma, M. Zhang, Y. Li, J. Shui, and Y. Zhou, "Allelopathy of rice (*Oryza sativa* L.) root exudates and its relations with *Orobancha cumana* Wallr. and *Orobancha minor* Sm. germination," *Journal of Plant Interactions*, vol. 9, no. 1, pp. 722–730, 2014.
- [14] Z. A. Cheema, M. Farooq, and A. Khaliq, "Application of allelopathy in crop production: success story from Pakistan," in *Allelopathy*, pp. 113–143, Springer, Berlin, Heidelberg, 2013.
- [15] K. Jabran, G. Mahajan, V. Sardana, and B. S. Chauhan, "Allelopathy for weed control in agricultural systems," *Crop Protection*, vol. 72, pp. 57–65, 2015.
- [16] A. A. Bajwa, A. Nawaz, and M. Farooq, "Allelopathic crop water extracts application improves the wheat productivity under low and high fertilizer inputs in a semi-arid environment," *International Journal of Plant Production*, vol. 14, no. 1, pp. 23–35, 2020.
- [17] S. O. Duke, F. E. Dayan, J. G. Romagni et al., "Natural products as sources of herbicides: current status and future trends," *Weed Research*, vol. 40, no. 1, pp. 99–111, Article ID 2119901, 2000.
- [18] Z. A. Cheema, M. Luqman, and A. Khaliq, "Use of allelopathic extracts of sorghum and sunflower herbage for weed control in wheat," *Journal of Animal and Plant Sciences*, vol. 79, no. 2-3, 112 pages, 1997.
- [19] P. Nikneshan, H. Karimmojeni, M. Moghanibashi, and N. al Sadat Hosseini, "Allelopathic potential of sunflower on weed management in safflower and wheat," *Australian Journal of Crop Science*, vol. 5, no. 11, Article ID 1434, 2011.

- [20] Z. A. Cheema and A. Khaliq, "Use of sorghum allelopathic properties to control weeds in irrigated wheat in a semi arid region of Punjab," *Agriculture, Ecosystems & Environment*, vol. 79, no. 2-3, pp. 105–112, 2000.
- [21] M. J. Ayeni and J. Kayode, "Allelopathic effects of aqueous extracts from residues of sorghum bicolor stem and maize inflorescence on the germination and growth of *Euphorbia heterophylla* L.," *Journal of Plant Studies*, vol. 2, no. 2, p. 1, 2013.
- [22] W. S. Jung, K. H. Kim, J. K. Ahn, S. J. Hahn, and I. M. Chung, "Allelopathic potential of rice (*Oryza sativa* L.) residues against *Echinochloa crus-galli*," *Crop Protection*, vol. 23, no. 3, pp. 211–218, 2004.
- [23] M. Kolahi, B. Peivastega, I. Hadizadeh, and S. Seyyedneja, "Inhibition of germination and seedling growth of wild oat by rice hull extracts," *Journal of Applied Sciences*, vol. 9, no. 15, pp. 2857–2860, 2009.
- [24] Z. A. Hassan, "Studies on the allelopathic potential of corn (*Zea mays* L.) aqueous extracts and root exudates," *Journal of Agricultural Science and Technology B*, vol. 2, pp. 432–437, 2012.
- [25] M. H. Shahrajabian, M. Khoshkham, W. Sun, and Q. Cheng, "Germination and seedlings growth of corn (*Zea mays* L.) to allelopathic effects of rice (*Oryza sativa* L.)," *Tropical Plant Research*, vol. 6, no. 1, pp. 152–156, 2019.
- [26] A. Koocheki, B. Lalegani, and S. A. Hosseini, "Ecological consequences of allelopathy," in *Allelopathy*, pp. 23–38, Springer, Berlin, Heidelberg, 2013.
- [27] J. M. Vivanco, H. P. Bais, F. R. Stermitz, G. C. Thelen, and R. M. Callaway, "Biogeographical variation in community response to root allelochemistry: novel weapons and exotic invasion," *Ecology Letters*, vol. 7, no. 4, pp. 285–292, 2004.
- [28] A. Torres, R. M. Oliva, D. Castellano, and P. Cross, *First World Congress on Allelopathy-A Science of the Future*, SAI (University of Cadiz), Cadiz, Spain, 1996.
- [29] C. H. Muller, "Allelopathy as a factor in ecological process," *Vegetatio*, vol. 18, no. 1-6, pp. 348–357, 1969.
- [30] F. A. Macias, A. Oliveros-Bastidas, D. Marín, C. Carrera, N. Chinchilla, and J. M. G. Molinillo, "Plant bio-communicators: their phytotoxicity, degradation studies and potential use as herbicide models," *Phytochemistry Reviews*, vol. 7, no. 1, pp. 179–194, 2007.
- [31] H. M. Ahmed, S. Nabavi, and S. Behzad, "Herbal drugs and natural products in the light of nanotechnology and nanomedicine for developing drug formulations," *Mini Reviews in Medicinal Chemistry*, vol. 21, no. 3, pp. 302–313, 2021.
- [32] N. Schandry and C. Becker, "Allelopathic plants: models for studying plant–interkingdom interactions," *Trends in Plant Science*, vol. 25, no. 2, pp. 176–185, 2019.
- [33] M. Kruse, M. Strandberg, and B. Strandberg, p. 315, 2000 *Ecological Effects of Allelopathic Plants-A Review* NERI Ministry of Environment and Energy, National Environmental Research Institute, Silkeborg, Denmark, Technical Report.
- [34] U. Blum, S. R. Shafer, and M. E. Lehman, "Evidence for inhibitory allelopathic interactions involving phenolic acids in field soils: concepts vs. an experimental model," *Critical Reviews in Plant Sciences*, vol. 18, no. 5, pp. 673–693, 1999.
- [35] A. R. M. AL-Tawaha and O. D. A. T. Nidal, "Use of sorghum and maize allelopathic properties to inhibit germination and growth of wild barley (*Hordeum spontaneum*)," *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, vol. 38, no. 3, pp. 124–127, 2010.
- [36] M. M. Hassan, H. M. Daffalla, S. O. Yagoub, M. G. Osman, M. E. A. Gani, and A. G. E. Babiker, "Allelopathic effects of some botanical extracts on germination and seedling growth of Sorghum bicolor L.," *Journal of Agricultural Technology*, vol. 8, no. 4, pp. 1423–1469, 2012.
- [37] S.-Y. Hong, L. Roze, and J. Linz, "Oxidative stress-related transcription factors in the regulation of secondary metabolism," *Toxins*, vol. 5, no. 4, pp. 683–702, 2013.
- [38] J. Ludwig-Müller, "Plants and endophytes: equal partners in secondary metabolite production?" *Biotechnology Letters*, vol. 37, no. 7, pp. 1325–1334, 2015.
- [39] D. A. Jacobo-Velázquez, M. González-Agüero, and L. Cisneros-Zevallos, "Cross-talk between signaling pathways: the link between plant secondary metabolite production and wounding stress response," *Scientific Reports*, vol. 5, no. 1, Article ID 8608, 2015.
- [40] R. M. Callaway and E. T. Aschehoug, "Invasive plants versus their new and old neighbors: a mechanism for exotic invasion," *Science*, vol. 290, no. 5491, pp. 521–523, 2000.
- [41] V. Kumar, D. C. Brainard, and R. R. Bellinder, "Suppression of Powell amaranth (*Amaranthus powellii*) by buckwheat residues: role of allelopathy," *Weed Science*, vol. 57, no. 1, pp. 66–73, 2009.
- [42] T. D. Khanh, T. D. Xuan, and I. M. Chung, "Rice allelopathy and the possibility for weed management," *Annals of Applied Biology*, vol. 151, no. 3, pp. 325–339, 2007.
- [43] M. A. Ebrahimzadeh, F. Pourmorad, and S. Hafezi, "Antioxidant activities of Iranian corn silk," *Turkish Journal of Biology*, vol. 32, no. 1, pp. 43–49, 2008.
- [44] J. Liu, C. Wang, Z. Wang, C. Zhang, S. Lu, and J. Liu, "The antioxidant and free-radical scavenging activities of extract and fractions from corn silk (*Zea mays* L.) and related flavone glycosides," *Food Chemistry*, vol. 126, no. 1, pp. 261–269, 2011.
- [45] L. Guo, J. Qiu, L.-F. Li, B. Lu, K. Olsen, and L. Fan, "Genomic clues for crop-weed interactions and evolution," *Trends in Plant Science*, vol. 23, no. 12, pp. 1102–1115, 2018.
- [46] M. A. Lewis, "Use of freshwater plants for phytotoxicity testing: a review," *Environmental Pollution*, vol. 87, no. 3, pp. 319–336, 1995.
- [47] S. Zuo, G. Liu, and M. Li, "Genetic basis of allelopathic potential of winter wheat based on the perspective of quantitative trait locus," *Field Crops Research*, vol. 135, pp. 67–73, 2012.
- [48] F. Cheng and Z. Cheng, "Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy," *Frontiers of Plant Science*, vol. 6, Article ID 1020, 2015.
- [49] D. P. Horvath, S. A. Hansen, J. P. Moriles-Miller et al., "RNAseq reveals weed-induced PIF3-like as a candidate target to manipulate weed stress response in soybean," *New Phytologist*, vol. 207, no. 1, pp. 196–210, 2015.
- [50] L. Guo, J. Qiu, C. Ye et al., "Echinochloa crus-galli genome analysis provides insight into its adaptation and invasiveness as a weed," *Nature Communications*, vol. 8, no. 1, pp. 1031–1110, 2017.
- [51] L. D. Holappa and U. Blum, "Effects of exogenously applied ferulic acid, a potential allelopathic compound, on leaf growth, water utilization, and endogenous abscisic acid levels of tomato, cucumber, and bean," *Journal of Chemical Ecology*, vol. 17, no. 5, pp. 865–886, 1991.
- [52] T. Tanaka, H. K. Abbas, and S. O. Duke, "Structure-dependent phytotoxicity of fumonisins and related compounds

- in a duckweed bioassay,” *Phytochemistry*, vol. 33, no. 4, pp. 779–785, 1993.
- [53] F. E. Dayan and S. O. Duke, “Biological activity of allelochemicals,” in *Plant-derived Natural Products*, pp. 361–384, Springer, New York, NY, 2009.
- [54] E. Galun and A. Breiman, “Quantitative assays of phytotoxins using plant protoplasts and isolated cells,” in *Plant Toxin Analysis*, pp. 33–50, Springer, Berlin, Heidelberg, 1992.
- [55] B. Truelove, D. E. Davis, and L. R. Jones, “A new method for detecting photosynthesis inhibitors,” *Weed Science*, vol. 22, no. 1, pp. 15–17, 1974.
- [56] R. D. Williams and R. E. Hoagland, “The effects of naturally occurring phenolic compounds on seed germination,” *Weed Science*, vol. 30, no. 2, pp. 206–212, 1982.
- [57] K. Javed, “Quantification of alkaloids, phenols and flavonoids in sunflower (*Helianthus annuus* L.),” *African Journal of Biotechnology*, vol. 10, no. 16, pp. 3149–3151, 2011.
- [58] C. Preece and J. Peñuelas, “A return to the wild: root exudates and food security,” *Trends in Plant Science*, vol. 25, no. 1, pp. 14–21, 2019.
- [59] M. Weih, U. M. E. Didon, A.-C. Rönnberg-Wästljung, and C. Björkman, “Integrated agricultural research and crop breeding: allelopathic weed control in cereals and long-term productivity in perennial biomass crops,” *Agricultural Systems*, vol. 97, no. 3, pp. 99–107, 2008.
- [60] C. C. Vigueira, K. M. Olsen, and A. L. Caicedo, “The red queen in the corn: agricultural weeds as models of rapid adaptive evolution,” *Heredity*, vol. 110, no. 4, pp. 303–311, 2013.
- [61] C. N. Stewart Jr, “Becoming weeds,” *Nature Genetics*, vol. 49, no. 5, pp. 654–655, 2017.
- [62] Integrated Crop Management, *International Survey of Herbicide Resistance Weeds*, Iowa State University, Ames, Iowa, 2016, <http://www.weedscience.org/Home.aspx>.
- [63] E.-C. Oerke, “Crop losses to pests,” *The Journal of Agricultural Science*, vol. 144, no. 1, pp. 31–43, 2006.
- [64] T. P. Michael and R. VanBuren, “Progress, challenges and the future of crop genomes,” *Current Opinion in Plant Biology*, vol. 24, pp. 71–81, 2015.
- [65] J. R. Qasem, “Applied allelopathy in weed management: an update,” in *Allelopathy*, pp. 251–297, Springer, Berlin, Heidelberg, 2013.
- [66] A. Scavo, A. Restuccia, C. Abbate, and G. Mauromicale, “Seeming field allelopathic activity of *Cynara cardunculus* L. reduces the soil weed seed bank,” *Agronomy for Sustainable Development*, vol. 39, no. 4, p. 41, 2019.
- [67] S. Sadeghi, A. Rahnavard, and Z. Y. Ashrafi, “Response of wheat (*Triticum aestivum*) germination and growth of seedling to allelopathic potential of sunflower (*Helianthus annuus*) and barley (*Hordeum vulgare* L.) extracts,” *Journal of Agricultural Technology*, vol. 6, no. 3, pp. 573–577, 2010.
- [68] M. Farooq, K. Jabran, Z. A. Cheema, A. Wahid, and K. H. Siddique, “The role of allelopathy in agricultural pest management,” *Pest Management Science*, vol. 67, no. 5, pp. 493–506, 2011.
- [69] M. Liebman and E. Dyck, “Crop rotation and intercropping strategies for weed management,” *Ecological Applications*, vol. 3, no. 1, pp. 92–122, 1993.
- [70] P. C. Bhowmik and Inderjit, “Challenges and opportunities in implementing allelopathy for natural weed management,” *Crop Protection*, vol. 22, no. 4, pp. 661–671, 2003.
- [71] D. Soltys, U. Krasuska, R. Bogatek, and A. Gniazdowska, “Allelochemicals as bioherbicides-present and perspectives,” in *Herbicides-Current Research and Case Studies in Use*, IntechOpen, London, UK, 2013.
- [72] M. B. Hufford, J. C. Berny Miery Teran, and P. Gepts, “Crop biodiversity: an unfinished magnum opus of nature,” *Annual Review of Plant Biology*, vol. 70, no. 1, pp. 727–751, 2019.
- [73] R. B. G. Kew, *State of the World’s Plants 2016*, Royal Botanic Garden, Kew, UK, 2016.
- [74] S. L. Pimm and P. H. Raven, “The fate of the world’s plants,” *Trends in Ecology & Evolution*, vol. 32, no. 5, pp. 317–320, 2017.
- [75] R. Dirzo and P. H. Raven, “Global state of biodiversity and loss,” *Annual Review of Environment and Resources*, vol. 28, no. 1, pp. 137–167, 2003.
- [76] K. Jabran and M. Farooq, “Implications of potential allelopathic crops in agricultural systems,” in *Allelopathy*, pp. 349–385, Springer, Berlin, Heidelberg, 2013.
- [77] M. Olofsdotter, L. B. Jensen, and B. Courtois, “Improving crop competitive ability using allelopathy - an example from rice,” *Plant Breeding*, vol. 121, no. 1, pp. 1–9, 2002.
- [78] M. L. Bouillant, C. Jacoud, I. Zanella, J. Favre-Bonvin, and R. Bally, “Identification of 5-(12-heptadecenyl)-resorcinol in rice root exudates,” *Phytochemistry*, vol. 35, no. 3, pp. 768–771, 1994.
- [79] I.-M. Chung, S.-J. Hahn, and A. Ahmad, “Confirmation of potential herbicidal agents in hulls of rice, *Oryza sativa*,” *Journal of Chemical Ecology*, vol. 31, no. 6, pp. 1339–1352, 2005.
- [80] H. Kato-Noguchi, “Barnyard grass-induced rice allelopathy and momilactone B,” *Journal of Plant Physiology*, vol. 168, no. 10, pp. 1016–1020, 2011.
- [81] Z. El Marsni, A. Torres, R. M. Varela et al., “Isolation of bioactive compounds from sunflower leaves (*Helianthus annuus* L.) extracted with supercritical carbon dioxide,” *Journal of Agricultural and Food Chemistry*, vol. 63, no. 28, pp. 6410–6421, 2015.
- [82] R. Farhoudi and D. J. Lee, “Allelopathic potential of sunflower (*Helianthus annuus*) water extracts to reduce the pendimethalin herbicide dose to control *Chenopodium album* in corn (*Zea mays*),” *Allelopathy Journal*, vol. 35, no. 1, 2015.
- [83] L. A. Weston, “Utilization of allelopathy for weed management in agroecosystems,” *Agronomy Journal*, vol. 88, no. 6, pp. 860–866, 1996.
- [84] R. G. Belz and K. Hurlle, “Differential exudation of two Benzoxazinoids One of the determining factors for seedling allelopathy of triticeae species,” *Journal of Agricultural and Food Chemistry*, vol. 53, no. 2, pp. 250–261, 2005.
- [85] C. I. Owuama, “Sorghum: a cereal with lager beer brewing potential,” *World Journal of Microbiology and Biotechnology*, vol. 13, no. 3, pp. 253–260, 1997.
- [86] G. Qi, N. Li, X. S. Sun, and D. Wang, “Overview of sorghum industrial utilization,” *Agronomy Monographs*, vol. 58, pp. 463–476, 2019.
- [87] P. Srinivasa Rao, W. Z. Lizarazu, D. Bellmer, and A. Monti, “Prospect of sorghum as a biofuel feedstock,” *Genetics, Genomics and Breeding of Sorghum*, vol. 303, 2014.
- [88] E. A. Khan, A. A. Khakwani, and A. Ghazanfarullah, “Effects of allelopathic chemicals extracted from various plant leaves on weed control and wheat crop productivity,” *Pakistan Journal of Botany*, vol. 47, no. 2, pp. 735–740, 2015.
- [89] M. R. Uddin, K. W. Park, J. Y. Pyon, and S. U. Park, “Combined herbicidal effect of two natural products (sorgoleone and hairy root extract of tartary buckwheat) on

- crops and weeds," *Australian Journal of Crop Science*, vol. 7, no. 2, p. 227, 2013.
- [90] J. A. Rasmussen, A. M. Hejl, F. A. Einhellig, and J. A. Thomas, "Sorgoleone from root exudate inhibits mitochondrial functions," *Journal of Chemical Ecology*, vol. 18, no. 2, pp. 197–207, 1992.
- [91] M. A. Czarnota, R. N. Paul, F. E. Dayan, C. I. Nimbal, and L. A. Weston, "Mode of action, localization of production, chemical nature, and activity of sorgoleone: a potent PSII inhibitor in sorghum spp. root Exudates1," *Weed Technology*, vol. 15, no. 4, pp. 813–825, 2001.
- [92] V. M. Gonzalez, J. Kazimir, C. Nimbal, L. A. Weston, and G. M. Cheniae, "Inhibition of a photosystem II electron transfer reaction by the natural product sorgoleone," *Journal of Agricultural and Food Chemistry*, vol. 45, no. 4, pp. 1415–1421, 1997.
- [93] A. M. Hejl and K. L. Koster, "The allelochemical sorgoleone inhibits root H⁺-ATPase and water uptake," *Journal of Chemical Ecology*, vol. 30, no. 11, pp. 2181–2191, 2004.
- [94] C. I. Nimbal, C. N. Yerkes, L. A. Weston, and S. C. Weller, "Herbicidal activity and site of action of the natural product sorgoleone," *Pesticide Biochemistry and Physiology*, vol. 54, no. 1, pp. 73–83, 1996.
- [95] N. M. Correia, M. D. C. Centurion, and P. D. C. Alves, "Influence of sorghum aqueous extracts on soybean germination and seedling development," *Ciência Rural*, vol. 35, no. 3, pp. 498–503, 2005, (Brazil).
- [96] C. S. Park, G. D. Marx, Y. S. Moon, D. Wiesenborn, K. C. S. Chang, and V. L. Hofman, "Alternative uses of sunflower," *Agronomy Monographs*, vol. 35, pp. 765–807, 2015.
- [97] Z. Muhammad and A. Majeed, "Allelopathic effects of aqueous extracts of sunflower on wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.)," *Pakistan Journal of Botany*, vol. 46, no. 5, pp. 1715–1718, 2014.
- [98] P. Nikneshan, H. Karimmojeni, M. Moghanibashi, and N. al Sadat Hosseini, "Allelopathic potential of sunflower on weed management in safflower and wheat," *Australian Journal of Crop Science*, vol. 5, no. 11, Article ID 1434, 2011.
- [99] T. Anjum and R. Bajwa, "Screening of sunflower varieties for their herbicidal potential against common weeds of wheat," *Journal of Sustainable Agriculture*, vol. 32, no. 2, pp. 213–229, 2008.
- [100] E. Pannacci, D. Pettorossi, and F. Tei, "Phytotoxic effects of aqueous extracts of sunflower on seed germination and growth of *Sinapis alba* L., *Triticum aestivum* L. and *Lolium multiflorum* Lam," *Allelopathy Journal*, vol. 32, no. 1, p. 23, 2013.
- [101] M. K. Amb and A. S. Ahluwalia, "Allelopathy: potential role to achieve new milestones in rice cultivation," *Rice Science*, vol. 23, no. 4, pp. 165–183, 2016.
- [102] H. Kato-Noguchi and R. J. Peters, "The role of momilactones in rice allelopathy," *Journal of Chemical Ecology*, vol. 39, no. 2, pp. 175–185, 2013.
- [103] L.-X. You, P. Wang, and C.-H. Kong, "The levels of jasmonic acid and salicylic acid in a rice-barnyardgrass coexistence system and their relation to rice allelochemicals," *Biochemical Systematics and Ecology*, vol. 39, no. 4–6, pp. 491–497, 2011.
- [104] H. He, H. Wang, C. Fang et al., "Barnyard grass stress up regulates the biosynthesis of phenolic compounds in allelopathic rice," *Journal of Plant Physiology*, vol. 169, no. 17, pp. 1747–1753, 2012.
- [105] I. M. Chung, J. K. Ahn, and S. J. Yun, "Assessment of allelopathic potential of barnyard grass (*Echinochloa crus-galli*) on rice (*Oryza sativa* L.) cultivars," *Crop Protection*, vol. 20, no. 10, pp. 921–928, 2001.
- [106] C.-H. Kong, F. Hu, P. Wang, and J.-L. Wu, "Effect of allelopathic rice varieties combined with cultural management options on paddy field weeds," *Pest Management Science*, vol. 64, no. 3, pp. 276–282, 2008.
- [107] F. A. O. Faostat, *Food and Agricultural Commodities Production 2008*, Food and Agriculture Organization of the United Nations, NY, USA, 2011.
- [108] R. Pandey, A. Singh, S. Maurya, U. P. Singh, and M. Singh, "Phenolic acids in different preparations of Maize (*Zea mays*) and their role in human health," *Int. J. Curr. Microbiol. App. Sci*, vol. 2, no. 6, pp. 84–92, 2013.
- [109] J. Strable and M. J. Scanlon, "Maize (*Zea mays*): a model organism for basic and applied research in plant biology," *Cold Spring Harbour Protocols*, vol. 2009, no. 10, pp. pdb.emo132–emo132, 2009.
- [110] S. A. Ashok, "Phytochemical and pharmacological screening of wheatgrass juice (*Triticum aestivum* L.)," *International Journal of Pharmaceutical Sciences Review and Research*, vol. 9, no. 1, pp. 159–164, 2011.
- [111] K. R. Krishna, *Maize Agroecosystem: Nutrient Dynamics and Productivity*, CRC Press, FL, USA, 2012.
- [112] R. E. Neild and J. E. Newman, *Growing Season Characteristics and Requirements in the Corn Belt*, Iowa State University, Ames, Iowa, Cooperative Extension Service, 1987.
- [113] J. Yan, M. Warburton, and J. Crouch, "Association mapping for enhancing maize (*Zea mays*L.) genetic improvement," *Crop Science*, vol. 51, no. 2, pp. 433–449, 2011.
- [114] S. M. Mohsen and A. S. M. Ammar, "Total phenolic contents and antioxidant activity of corn tassel extracts," *Food Chemistry*, vol. 112, no. 3, pp. 595–598, 2009.
- [115] B. V. Owoyele, M. N. Negedu, S. O. Olaniran et al., "Analgesic and anti-inflammatory effects of aqueous extract of *Zea mays* husk in male Wistar rats," *Journal of Medicinal Food*, vol. 13, no. 2, pp. 343–347, 2010.
- [116] F. R. Hay, N. R. S. Hamilton, B. J. Furman, H. D. Upadhyaya, K. N. Reddy, and S. K. Singh, "Cereals," in *Conservation of Tropical Plant Species*, pp. 293–315, Springer, New York, NY, USA, 2013.
- [117] A. S. Tsiftaris, "The biology of maize (*Zea mays*, L.)," *The Journal of Agricultural Sciences*, vol. 21, no. 7, pp. 434–436, 1995.
- [118] M. D. Richardson and C. W. Bacon, "Cyclic hydroxamic acid accumulation in corn seedlings exposed to reduced water potentials before, during, and after germination," *Journal of Chemical Ecology*, vol. 19, no. 8, pp. 1613–1624, 1993.
- [119] A. L. Neal, S. Ahmad, R. Gordon-Weeks, and J. Ton, "Benzoxazinoids in root exudates of maize attract *Pseudomonas putida* to the rhizosphere," *PLoS One*, vol. 7, no. 4, Article ID e35498, 2012.
- [120] H. Kato-Noguchi, Y. Sakata, K. Takenokuchi, S. Kosemura, and S. Yamamura, "Allelopathy in maize I.: isolation and identification of allelochemicals in maize seedlings," *Plant Production Science*, vol. 3, no. 1, pp. 43–46, 2000.
- [121] M. A. Konstantopoulou, F. D. Krokos, and B. E. Mazomenos, "Chemical composition of corn leaf essential oils and their role in the oviposition behavior of *sesamia nonagrioides* females," *Journal of Chemical Ecology*, vol. 30, no. 11, pp. 2243–2256, 2004.
- [122] M. Frey, K. Schullehner, R. Dick, A. Fiesselmann, and A. Gierl, "Benzoxazinoid biosynthesis, a model for evolution

- of secondary metabolic pathways in plants,” *Phytochemistry*, vol. 70, no. 15-16, pp. 1645–1651, 2009.
- [123] M. Panahyan-e-Kivi, A. Tobeh, M. A. Shahverdik, and S. Jamaati-Esomarin, “Inhibitory impact of some crop plants extracts on germination and growth of wheat,” *American-Eurasian Journal of Agricultural & Environmental Sciences*, vol. 9, no. 1, pp. 47–51, 2010.
- [124] R. Zhang, H. Zhang, C. Tu et al., “Phytotoxicity of ZnO nanoparticles and the released Zn(II) ion to corn (*Zea mays* L.) and cucumber (*Cucumis sativus* L.) during germination,” *Environmental Science and Pollution Research*, vol. 22, no. 14, pp. 11109–11117, 2015.