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Plant extracts - importance in sustainable agriculture

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Highlights

- *Higher plants constitute a rich source of various bioactive compounds for the production of useful natural products.*
- *The importance of the proper choice of extraction method and solvent to process and preserve the desired substances.*
- *Plant extracts as biostimulants and plant protection products for use in modern and sustainable agriculture.*
- *The positive effects of plant-based extracts on plants cultivated under normal and unfavourable conditions.*
- *Plant extracts as a new generation of eco-friendly products for the increment of the production of high-quality food.*

Abstract

Plants due to the high content of various bioactive compounds are the main raw material for production of valuable, and useful bio-products (*e.g*., food, cosmetics, medicines, biostimulants, biopesticides, and feed). Different plant parts, for instance: seeds, fruits, flowers, stems, leaves, and roots can be used for their manufacture. Nowadays, there is a clear need to develop new, efficient, and environmentally safe methods of stimulation of plant, growth and crop protection. Plant-based extracts are new, natural, and multi-compounds products that could be used for these purposes. They possess antifungal, antimicrobial, antiparasitic, antiprotozoal, antioxidant, medicinal, aromatic, and anti-inflammatory properties. This group of natural products has the potential to become a new generation of bio-products suitable for use in sustainable agriculture. The purpose of this review is to provide an overview of the literature describing the impact of plant-derived extracts/biostimulants (PDBs) on crops grown in controlled, and real conditions as well as under various abiotic and biotic stresses; the extraction methods used to obtain PDBs, and the specific constituents responsible for their biostimulating activity. The application of these bio-products could be beneficial for sustainable production, due to several advantages, such as low toxicity to humans and the environment, enhanced resistance of cultivated plants to biotic and abiotic stress, increased yields and quality of crops, as well as the reduction in the use of mineral fertilisers and pesticides. However, deeper cooperation between industrial and academic research is required to accelerate the development of new environmentally safe solutions for future agriculture.

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Introduction

Currently, horticulture has to face major challenges related to the provision of a sufficient quantity of healthy food for a constantly increasing world population (Povero *et al*., 2016; Colla *et al*., 2017; Parađiković *et al*., 2018; Rouphael and Colla, 2018; Di Mola *et al*., 2019; Zulfiqar *et al*., 2019; Dipak Kumar and Aloke, 2020). Taking into account decreasing arable areas and approaching the limits of genetic potential of crops, the only solution to achieve this is the enhancement of crop yield and its protection (Povero *et al*., 2016). It is important to produce high-quality nutritious food which could help in the protection against hunger and malnutrition (Povero *et al*., 2016; Zulfiqar *et al*., 2019; Dipak Kumar and Aloke, 2020).

The growing demand for sustainable food, feed, fuel, and fibre to decrease the depletion of resources and the degradation of the ecosystems, requires the adoption of more sustainable management of the agricultural land areas. The efforts should be geared towards decreasing the input costs, as well as the dependence on chemical fertilisers and pesticides, the misuse of which may pose multiple threats to human life and the environment (Bulgari *et al*., 2015; Colla *et al*., 2017; Parađiković *et al*., 2018; Rouphael and Colla, 2018; Di Mola *et al*., 2019; Zulfiqar *et al*., 2019; Dipak Kumar and Aloke, 2020). From this point of view, farmers and researchers are called to find alternative solutions to increase agricultural productivity preserving natural resources and in particular reducing land use. Alternative and sustainable approaches to overcome these issues are therefore extensively investigated (Colla *et al*., 2017; Parađiković *et al*., 2018; Zulfiqar *et al*., 2019; Rouphael and Colla, 2020). Several strategies have been proposed and among them, organic products called *biostimulants* are the most investigated and promising products to make agriculture more sustainable. The use of plant-derived biostimulants (PDBs) represents an eco-friendly, efficient technology or complement to their synthetic counterparts (Ertani *et al*., 2015, 2016; De Pascale *et al*., 2017; Parađiković *et al*., 2018; Rouphael and Colla, 2018, 2020; Dipak Kumar and Aloke, 2020).

The European authorities to safeguard humans, plants, animals and the environment sustainability made available a recent European Regulation, known as Regulation (EU) 2019/1009, to regulate the use of fertilisers and harmonise the market for the production of these compounds including biostimulants. In the Regulation (EU) 2019/1009 plant biostimulant is defined as *a product stimulating plant nutrition processes independently of the product's nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere as: i) nutrient use efficiency; ii) tolerance to abiotic stress; iii) quality traits and iv) availability of confined nutrients in soil or rhizosphere* (EU, 2019) following the definition provided by du Jardin (2015). Based on this definition, plant biostimulant is defined based on agricultural performances, including different bioactive natural substances: i) humic and fulvic acids; ii) animal and vegetal protein hydrolysates; iii) macroalgae seaweeds extracts; and iv) silicon, as well as beneficial microorganisms: i) arbuscular mycorrhizal fungi; and ii) bacteria belonging to the genera *Rhizobium*, *Azotobacter*, and *Azospirillum* (EU, 2019).

Nowadays, farmers and researchers put high attention to biostimulant to improve agricultural sustainability, however, other natural products should be considered, studied, and assessed and the present review intends to highlight the importance of plant extract to improve agricultural sustainability and in particular crops quality and quantity. Primary and secondary plant metabolites affect important biological activities influencing plant physiological responses (Barrajón-Catalán *et al*., 2014) and plant phenotype. Several previous studies reported the effects of plant extracts on hormones (Lucini *et al*., 2018), organic acids (Abou Chehade *et al*., 2018), polyphenols (Lucini *et al*., 2018), and sugars (Abou Chehade *et al*., 2018) contents.

Crops quality (fruit size, colour, firmness, macro- and micronutrient contents, vitamins, polyphenols) and quantity (yield per square meter) traits are affected by both biotic and abiotic stresses (Di Vittori *et al*., 2018). Crops to overcome stresses, at a physiological level shift from the first metabolism to the second one, using their energy reserves instead of concentrating on yielding. To avoid this reduction of yield, different categories of plant protection products have been studied and applied. Following the recommendations of the European Union, synthetic plant protection products should be replaced by natural ones, to improve agricultural sustainability.

Recently, plant extracts were largely investigated as a practical approach to improve specific crop production sustainability and in particular to produce biostimulants. Despite its economic relevance, evidence on the large use of plant extracts to replace synthetic products like fungicides, pesticides, and herbicides are still poorly understood. Investigations of plant extracts as products to overcome both biotic and abiotic stresses remain largely unexploited. In light of this point, this is the first review that highlights the current research and future development priorities, examining the factors supporting their use for replacing synthetic products used to improve crop production.

The main objective of the present review is to report some of the current research and future development regarding the importance of plant extracts in agriculture. In particular, this review explores three important topics: i) methods of extraction of the plant biomass; ii) chemical composition of plant extracts; iii) effect of plant-based biostimulants on plant growth, development, and quality cultivated under normal conditions, as well as exposed to biotic and abiotic stress. The information reported in this review may support the design of cropping systems where agricultural sustainability is enhanced by the use of plant extract as an alternative to synthetic plant protection products.

Materials and methods

This review concerns publications from the Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar databases, published in the last twenty years (2000-2020). Abstracts and articles were researched for their relevance to this review. In total, almost 180 papers were cited. In searching databases, the following keywords were checked: 'biostimulants', 'plant extract', 'botanical extract', 'herb extract', 'medicinal plant extract' in the topic and abstract of papers. Special attention was paid to the following researched topics: extraction of plant biomass; chemical composition of plant extracts; effect of plant-based biostimulants on plant growth, development, and quality cultivated under normal and stressful conditions. Table 1, presenting the methods of plant extracts production and their application in plant cultivation were limited only to experiments performed under greenhouse and field conditions.

The up-to-date literature review

Production of bio-products for agriculture

A variety of plants can be used to produce natural extracts. The biomass availability and wide abundance are the main selection criteria. Farmers or other growers (environmental agriculture) choose plants that grow near their farms (Roy *et al*., 2010; Mkenda *et al*., 2015; Pavela, 2016; Tembo *et al*., 2018). Additionally, the farmers know about their effectiveness (traditional recipes passed on for generations), the content of bioactive compounds and safety (Mkenda *et al*., 2015; Pavela, 2016; Tembo *et al*., 2018). An additional advantage of plant biomass is its low cost. Conversion of plant biomass into extracts, showing the action of biostimulants of plant growth or biopesticides, can be crucial for poor farmers in developing countries who cannot afford synthetic biostimulants, plant protection products due to their high costs (Fite *et al*., 2020). The importance of using readily available and cheap natural resources for plant cultivation should be emphasised (Jang and Kuk, 2019).

The choice of biomass for extraction depends mainly on its common occurrence in a given area. As a raw material, mainly medicinal plants, herbs, vegetables, shrubs, trees (*e.g*., stem, leaves, needles) are selected (Table 1). Agricultural waste such as rice straw, cereal straw, soybean leaf and stem, as well as waste products from other processes, for example, rice and barley hulls and bran being the by-products of the milling process can also constitute the raw material for extraction (Jang and Kuk, 2019). An interesting approach is presented by some scientists, who use common weeds for the production of biopesticides, *e.g*., insecticide (Roy *et al*., 2010; Mkenda *et al*., 2015; Green *et al*., 2017; Tembo *et al*., 2018). Table 1 presents the examples of the plant biomass extraction and the mode of application of the obtained extracts with their doses in plant cultivation (edible plants used by humans as food, mainly cereals, vegetables, and fruits grown in the greenhouse or in the field). Appropriately selected extraction technique of plant biomass provides a high content of biologically active compounds in the extract that stimulate plant growth and are active against plant disease pathogens and other pests, as well as abiotic stress. One of the first steps is the adequate preparation of the raw material for extraction. The biomass from each harvest is usually mixed before drying to ensure uniformity. Generally, plants are air-dried under shade to protect active compounds from degradation, then crushed using a mill, and finally sieved to obtain fine powder (Tembo *et al*., 2018). Air-dried and ground biomass is used as a raw material for extraction. As can be seen from Table 1, in the case of plant extracts, traditional, simple extraction methods with water as a solvent prevail, so that they can be used on a large scale and should not create difficulties for farmers. This is in contrast to other raw materials which are used to produce biostimulants of plant growth, such as algae/seaweeds, where more advanced extraction techniques are often used to extract biologically active compounds. Such methods include enzyme-assisted extraction, microwave-assisted extraction, pressurised liquid extraction, supercritical fluid extraction, ultrasound-assisted extraction, *etc*. Classical extraction techniques like maceration, shaking, Soxhlet extraction use large volumes of organic solvents and are considered time-consuming (Michalak and Chojnacka, 2014; EL Boukhari *et al*., 2020). In the case of plant extracts, more advanced extraction methods are used to analyse the biological properties of extracts *in vitro* tests - bioassays in the laboratory (*e.g*., Li and Zhihui, 2009; Wei *et al*., 2011; Cruz-Estrada *et al*., 2013; Green *et al*., 2017; Findura *et al*., 2020a), less advanced extraction methods relate to field trials. Plant extracts examined in the pot (greenhouse) or field trials are mainly produced by soaking the biomass in solvent (*e.g*., Cheema and Khaliq, 2000; Cheema *et al*., 2009; Alao and Adebayo, 2015; Farooq *et al*., 2017; Desoky *et al*., 2019a; Kayange *et al*., 2019; Rashid *et al*., 2020), shaking the biomass with solvent (*e.g*., Oparaeke, 2007; Roy *et al*., 2010; Onunkun, 2012), and homogenisation of the biomass in solvent (*e.g*., Wei *et al*., 2011; Hayat *et al*., 2016; Shah *et al*., 2017; Ali *et al*., 2019) at room temperature. In addition to the mentioned methods, the extraction of plant biomass can also be carried out by boiling in water or elevated temperatures and by fermentation (Oparaeke, 2007; Desoky *et al*., 2019a, 2019b Jang and Kuk, 2019; Findura *et al*., 2020a). More advanced extraction techniques are used in the case of isolation of a given biologically active compounds from plant biomass. For example, Jadeja *et al*. (2011) used Pressurised Hot Solvent Extraction to extract azadirachtin from neem (*Azadirachta indica*), having natural insecticide properties.

The predominant solvent in biomass extraction is water. First of all, the production of water extracts is one of the easiest methods and serves the purposes of the end-user - farmers (Roy *et al*., 2010). Secondly, water is an alternative to organic solvents used in conventional extraction techniques whose residues may remain on cultivated plants (Li and Zhihui, 2009). Water extracts have many advantages such as are eco-friendly, easily degradable, are not persistent in the soil, and are not toxic to animals and humans (Li and Zhihui, 2009). In some cases, organic solvents such as ethanol and methanol are used to obtain plant extracts (Basra and Lovatt, 2016; Kole *et al*., 2016; Green *et al*., 2017; Zuleta-Castro *et al*., 2017; Desoky *et al*., 2018a, 2018b; Jang and Kuk, 2019; Kaab *et al*., 2020). Ethanol is applied for the extraction of botanical active substances because is characterised by low toxicity and is approved by the food industry (Zuleta-Castro *et al*., 2017). After extraction, the solvent is evaporated. In the case of plant extracts obtained with organic solvents, an appropriate formulation should be prepared for application to plants. These formulations are composed for example from the extract, water, castor oil, and surfactant - Tween 80 (polyethylene glycol sorbitan monooleate) (Zuleta-Castro *et al*., 2017). In the case of methanolic extract, which was applied as a bioherbicide, the plant extract was mixed with vegetable oil of hazelnut, ethoxylated castor oil, surfactant - Tween 20 (polyethylene glycol sorbitan monolaurate), adjuvant UEP-100, ethanol, and water (Kaab *et al*., 2020). In the work of Kole *et al*. (2016), methanolic leaf extracts were mixed with surfactants - Na-alkaline sulfonate or K-alkaline sulfonate. Prepared formulations contain amphiphilic substances to mix the hydrophilic extract with the hydrophobic vegetable oil (Kaab *et al*., 2020). Mixing the plant extract with vegetable oil aims to facilitate the effective and complete penetration of the spray solution with active compounds by epidermal waxes (Kaab *et al*., 2020).

There are several methods of natural extracts application in plant growth - seed priming, medium (soil) supplementation, and foliar spray (Batool *et al*., 2016), but the last one is the most popular. Therefore, the obtained extracts are usually thoroughly filtered to remove the plant residues, which can accidentally clog the sprayer (Tembo *et al*., 2018). The most commonly used extract concentrations are those up to 10% (Table 1). Due to inexpensive raw material and easy extraction methods, plants and their compounds can be eco-friendly alternatives to commercial biostimulants of plant growth and pesticides. Based on the examples in Table 1, it can be seen that the extracts are mainly used as insecticides, fungicides, and herbicides. Many issues related to the use of plant extracts in sustainable agriculture require further investigation. First of all, to prepare effective formulations, bioactive compounds extracted from the plant biomass must be accurately identified and their biological activity comprehensively evaluated (Ali *et al*., 2019). The standardisation of plant extracts based on active ingredients, quality control and regulatory approval of botanicals are also key issues to consider (Isman, 1995). It is also recommended to perform an organoleptic assessment of harvested plant parts to exclude an undesired flavour, which may be derived from the used extract, *e.g*., garlic (Portz *et al*., 2008).

Chemical composition of plant extracts

Botanical extracts can act as natural biostimulants of plant growth or biopesticides because they represent a rich source of bioactive compounds. However, the detailed composition of plant extracts, especially used in field trials, remains to be investigated. The chemical composition of the biomass itself is studied much more often than the obtained extracts.

Generally, the stimulating properties of plant extracts are attributed to organic compounds such as polyphenols, amino acids, plant hormones, and vitamins, as well as micro- and macroelements. The composition of *Moringa oleifera* extract is well known and quite often studied by scientists.

This extract contains antioxidants and osmoprotectants: phe-

Table 1. Extraction methods of plants biomass and the application of extracts in plant cultivation.

Plant species	Extraction method	Method of application	Tested cultivars	Effects on crops	Reference
A) Plant extracts under normal conditions					
St. John's wort (*Hypericum perforatum*), giant goldenrod (*Solidago gigantea*), common dandelion (*Taraxacum officinale*), red clover (*Trifolium pratense*), nettle (*Urtica dioica*), valerian (*Valeriana officinalis*)	Ultrasound assisted extraction, dried and ground biomass, deionized water (1:20, *w/v*), 30 min, centrifugation; mechanical homogenization, 1 min, 28 000 rpm, centrifugation	Field, foliar application, 0.5%	Celeriac (*Apium graveolens*)	Increased the yield of leaves rosettes and roots, the weight of leaves rosettes and roots, the content of chlorophyll $a + b$ and carotenoids, the greenness index of leaves, the content of vitamin C in leaves and roots; mostly decreased the content of polyphenols and antioxidant activities in leaves but increased in roots; mostly increased the content of nitrates in leaves but decreased in roots; showed a varied impact on the content of micro and macroelements, the composition of volatile compounds and fatty acids	Godlewska *et al.*, 2020b
Garlic (*Allium sativum*)	Garlic cloves mixed with tap water (250 g/250 mL), freeze for 1 day, thawing, repetition of freezing and thawing three times, addition of water to 1 L, filtration	Field, foliar application, 5%	Faba bean (*Vicia faba*)	Increase in the content of photosynthetic pigments, indole acetic acid, phenolics, carbohydrate constituents, free amino acids, proline, the quantity of faba bean cultivars	Mohamed *et al.*, 2020
Garlic (*Allium sativum*)	10 g of fresh garlic ground in a mortar and pistil, homogenization in 100 mL of distilled water, centrifugation, filtration	Plastic tunnel, foliar spray, 0.2 mg/mL	Eggplant (*Solanum melongena*)	One pre-transplant spraying - improved growth, plant morphology and biomass, enhanced antioxidant enzymes (superoxide dismutase, peroxidase), photosynthesis and chlorophyll content; triple application - inhibited plant growth and development, lipid peroxidation (increased content of MDA); post-transplant application - increased growth, lack of significant increase in the MDA content	Ali *et al.*, 2019
Garlic (*Allium sativum*)	Fresh cloves mixed with distilled water (50 g/500 mL), blender, 15 min, filtration	Field, foliar spray 1:10, 1:20, 1:40	Snap bean (*Phaseolus vulgaris* cv. paulista)	Enhanced height, leaf area, leaves number, plant weight, flowers number, leaf and pod chemical compositions; increased number of pods, pod fresh weight, total pod yield	Elzaawely *et al.*, 2018
Chinese chive (*Allium tuberosum*), soybean leaves, soybean stems	50 g of ground material; water extract - the biomass mixed with 1 L of distilled water, 24 h; ethanol extract - the biomass mixed with 1 L of ethanol, 24 h; boiled extract - the biomass mixed with 1 L of distilled water, boiling 100°C, 30 min, fermentation extract - the biomass mixed with 500 mL of distilled water, stored at room temp., 14 days in the dark	Pots/greenhouse, foliar spray, 5%, (5 mL/pot)	Lettuce (*Lactuca sativa*)	Increased growth promotion	Jang and Kuk, 2019
Moringa leaf (*Moringa oleifera*)	Young leaves, frozen, homogenization in 80% ethanol (33 g/100 mL), extraction - continuous shaking, 4°C, 18 h, centrifugation, solvent evaporation	Pots/greenhouse, root and foliar application, 3.3% (*w/v*)	Cherry tomato (*Solanum lycopersicum*)	Increased canopy biomass and root, lateral vegetative shoot number, plant height, floral shoot number, number of flowers and fruits, yield as grams of fruit per plant, fruit concentrations of soluble sugars, protein, antioxidants, and lycopene, leaf concentrations of protein, proline, arginine, total antioxidants	Basra and Lovatt, 2016
Moringa leaf (*Moringa oleifera*)	Air-dried leaves, ground, extraction with ethyl alcohol, 50, 100, 200 and 300 g/L, shaking, 4 h, filtration, solvent evaporation	Field, foliar spray, dilution of the supernatants with distilled water, addition of surfactant 0.1% (v/v) Tween-20, 50, 100, 200, 300 g/L	Coriander (*Coriandrum sativum*)	Increased fruit yield, volatile oil yield, oil components, percentages of N, P, K, total sugars, the radical scavenging activity and total phenolic content	Mazrou, 2019
Moringa leaf (*Moringa oleifera*)	Soaking of powder air-dried leaves in water (100 g/L), 24 h, filtration	Orchard, foliar spray, dilution of the extract with water, addition of 0.01% Tween-20, 4, 5, 6%	Five years old of plum trees (*Prunus salicina*)	Increased setting, yield, fruit weight, firmness, colour, soluble solids content, titratable acidity ratio, ascorbic acid, anthocyanin content, antioxidant activity contents; reduced titratable acidity with reduced fruit drop	Thanaa *et al.*, 2017

Moringa leaf (*Moringa oleifera*)	Rinsed with water leaves kept in a freezer, overnight, mechanical extraction	Pot experiments (wire house), priming, foliar spray, 3%	Wheat (*Triticum aestivum*)	Improved speed and spread of emergence, seedling vigour (shoot and root length, fresh and dry weight), final emergence count; reduced time emergence, mean emergence time; improved emergence index	Khan *et al.*, 2017
Moringa leaf (*Moringa oleifera*)	Young leaves mixed with 80% ethanol (20 g/675 mL), stirring with a homogenizer, filtration	Field trials in sandy soil, foliar spraying, 1, 2, 3, 4%	Pea plants (*Pisum sativum*)	Increased fresh pods yield, shoot and seeds dry weight, biological yield, 100 seed weight, yield efficiency, protein content and nutrient accumulation, photosynthetic pigments content	Merwad, 2018
Moringa leaves, twigs (*Moringa oleifera*)	Aqueous extract prepared with distilled water	Pot experiments, foliar spray, 1, 2, 3%	Rocket (*Eruca vesicaria* subsp. *sativa*)	Increased plant height, fresh and dry weight, photosynthetic rates, stomatal conductance, the amounts of chlorophyll *a* and *b*, carotenoids, total sugars, total protein, phenols, ascorbic acid, N, P, K, Ca, Mg, Fe, growth promoting hormones (auxins, gibberellins, cytokinins); reduced the levels of lipid peroxidation and abscisic acid, the activities of the antioxidant enzymes (catalase, peroxidase and superoxide dismutase)	Mona, 2013
Licorice root (*Glycyrrhiza glabra*)	Dried root biomass soaked in water (100 g/20 L), 50°C, 24 h, filtration,	Field, seed soaking, foliar spray, dilution till 20 L with distilled water, Tween-20 addition, 0.5%	Common bean (*Phaseolus vulgaris*)	Plant growth, yield, relative water content, chlorophylls content were not altered	Rady *et al.*, 2019
Licorice root (*Glycyrrhiza glabra*)	Dried licorice roots ground and sifted, mixed with distilled water, 15 min, 50°C, the mixture was left for 24 h to settle, filtration	Field, foliar spraying, 5, 10 and 15 g/L	Onion (*Allium cepa*)	Increased plant height, length of the tallest leaf, number of leaves, flowering, seed production, germination percentage	Babilie *et al.*, 2015
Licorice root (*Glycyrrhiza glabra*)	Roots blended in distilled water (5 g or 10 g/L), 50°C, 24 h, filtration	Field, foliar application, 5, 10 g/L	Almond (*Prunus amygdalus* Batsch)	Improved vegetative growth characteristics, increased stem length and diameter, number of branches and leaves/seedling, leaf area, shoot fresh and dry weight, the total chlorophyll, leaf fresh and dry weight, N, Mn, Fe, Zn content	Thanaa *et al.*, 2016
Licorice root (*Glycyrrhiza glabra*)	Dried powdered roots extracted with distilled water (cold and hot) (10 g/L), filtration	Field, foliar application, 2 g of alcoholic and acetone extracts mixed with drops of Tween and filled into 1 L of distilled water	Fennel (*Foeniculum valgare*)	Improved growth, essential oil and chemical composition	El-Azim *et al.*, 2017
Red grape skin (*Vitis vinifera*) Blueberry fruits (*Vaccinium vitis-idaea*) Hawthorn leaves (*Crataegus monogina*)	Hawthorn - fully controlled enzymatic hydrolysis, the red grape skin material and blueberry fruits - cool extraction	Pot experiments (aerated complete culture solution; climatic chamber), hydroponic solution (48 h), 0.1, 1 mL/L	Maize (*Zea mays*)	Increased root and leaf biomass, chlorophyll, phenol acids and sugars content; induced phenylalanine ammonia lyase (PAL) activity	Ertani *et al.*, 2016
Common mugwort (*Artemisia vulgaris*)	Mixing of dried biomass with water (5 g/250 mL), 100°C, left under cover, 30 min, 20°C, after cooling down, washing the material, maceration of dried biomass in water (5 g/100 mL), 20°C, 24 h, filtration	Pot experiment (controlled environmental conditions), spray	Potato	Increased the chlorophyll *a* and chlorophyll *b* content and its total concentration, the carotenoids content; induced in plants the changes in the concentration of polyphenols	Findura, *et al.*, 2020b
Olive leaves (*Olea europaea*), pomegranate leaves (*Punica granatum*), common guava leaves (*Psidium guajava*)	Biomass washed with fresh water, dried, hand crushed, powdered, heated with sterile distilled water in a ratio 1:100 (*w/v*), 60°C, 45 min, filtration	Field, foliar spray, 5 g/L	Sesame (*Sesamum indicum*)	Increased carotenoids, total carbohydrates and lipids content, amylase and peroxidase activities; exerted a varied influence on fresh and dry weight of shoots, fresh weight of roots, shoots and roots length, number and weight of pods and seeds per plant, number of leaves, content of chlorophyll, content of carbohydrates in shoots, content of proteins in roots and shoots; decreased dry weight of roots, protease and catalase activities, total proteins content	Amin, 2018

Sugar beet (*Beta vulgaris*)	Biomass washed, juice extracted using an electric extractor, filtration	Germination and pot experiments (natural environmental conditions), seed priming/soaking (12 h), 10, 20, 30, 40, 50%	Wheat (*Triticum aestivum*)	Improved plant growth, photosynthetic pigments, antioxidants' activities and nutrient homeostasis	Noman *et al.*, 2018
Lantana (*Lantana camara*)	Natural fermentation, fermentation with bacteria	Pot experiments (glasshouse), spray, 5, 10 mL/L	Green gram (*Vigna radiata*)	Increased plant height, number of leaves, dry matter, chlorophyll content, number and weight of pods per plant, number of seeds per pod, grain yield	Ganagi and Jagadeesh, 2018
Borage leaves and flowers (*Borago officinalis*)	Leaves minced, macerated in deionized water (500 g/L), 25 days, in the dark, room temperature, filtration	Pot experiments (glasshouse), foliar spray, 1, 10 mL/L	Lettuce (*Lactuca sativa*)	Enhanced primary metabolism, increased leaf pigments and photosynthetic activity, plant fresh weight, chlorophyll *a* fluorescence, total flavonoids and phenols, total protein levels, *in vitro* PAL specific activity, the levels of PAL-like polypeptides; prevented degradation and induced increase in photosynthetic pigments during storage; decreased ethylene content; lack of significant impact on nitrate and sugar level	Bulgari *et al.*, 2017
Cultivated tobacco leaves (*Nicotiana tabacum*), bael leaves (*Aegle marmelos*), fig tree leaves (*Ficus hispida*), hina leaves (*Lawsonia inermis*), Chinese chaste tree leaves (*Vitex negundo*), wild celery seeds (*Carum roxburghianum*), white jute seeds (*Corchorus capsularis*), mahogany seeds (*Swietenia macrophylla*), garlic bulb (*Allium sativum*)	Biomass dried (20-25 days), ground, mixed with tap water (100 g/L), 3 days, filtration	Field, spray, 100%	Eggplant (*Solanum melongena*)	*N. tabacum* leaves extract - increased resistance against pest attack; enhanced growth, yield and longevity of plant life; *A. sativum* bulb extract - very poor efficacy to protect leaves from pest attack; caused total inhibition of fruit production; *S. macrophylla* and *C. roxburghianum* seeds extracts - showed phytotoxicity and hampered the growth; *C. roxburghianum* - caused total inhibition of fruit production	Azad and Sarker, 2017
French oak chips (*Quercus sessiliflora*)	Commercial oak extract (Protea France S.A.S.) obtained by maceration of biomass in water at high temperature	Vineyard, foliar spray, 25 and 100%	8-year-old grapevines (*Vitis vinifera*)	Affected composition, lowered alcohol content and acidity, increased colour intensity and stability, lowered shade, increased content of polyphenols	Pardo-García *et al.*, 2014
Apple seeds, colza seeds, rice husks	Not available	Orchard, foliar spray	Kiwifruit (*Actinidia deliciosa*)	Increased the fruit weight, ascorbic acid content, dry matter, antioxidant capacity	Donno *et al.*, 2013
Maize grains	Maize grains covered under wetted cotton until were mushy, grounding with distilled water, filtration; residues on the filter paper were extracted with ethyl alcohol (95%), 72 h, filtration, solvent evaporation; mixing the aqueous and alcoholic extracts	Pot experiments, soaking in 3% extract and spraying with 1 mm Mg plants	Sunflower seed (*Helianthus annuus*)	Elevated growth traits, plant water status and membrane stability index; reduced electrolyte leakage; improved leaf content of chlorophylls, carotenoids, total soluble sugars and proline, activities of non-enzymatic and enzymatic antioxidants; enhanced uptake of N, P, K, Mg, IAA, GA_3, zeatin; increased seed yield and oil content - oleic and linoleic fatty acids; decreased other saturated, monounsaturated, polyunsaturated fatty acids; improved seed, seedling vigour traits	Rehman *et al.*, 2018
Myrtle, Orang, Myrtle + Orang	Shoots of biomass soaked in distilled water (10 g/100 mL), 48 h, 24°C, filtration, centrifugation	Pot experiments (glasshouse), irrigation	Pepper (*Capsicum frutescens*), eggplant (*Solanum mebngena*)	Increased the percentage of germination, root length, root dry weight, leaf area	Abbas and Hussain, 2020
Rosemary	Steam-distillation of dried material, 90 min - extraction of oil	Lime soil, greenhouse conditions, foliar spray - 500 or 1000 mg/L oil, soil application - 500 µL oil/kg of soil	Tomato (*Lycopersicon esculentum*)	1000 mg/L - reduced plant height, increased leaf SPAD value, shoot and root fresh weights, leaf soluble carbohydrates, nutrient content (N, K, Mg, Fe and Zn) in leaves; 500 mg/L and soil application - higher root fresh weight than in control plants	Souri and Bakhtiarizade, 2019
Rosemary (*Rosmarinus officinalis*), eucalyptus (*Eucalyptus globulus*)	Commercial product - 'Agriculture Green-tech E', Meydan Solution Ltd, Larnaca, Cyprus	Pot experiments, foliar spray at 2% once (EP-1) and every 20 days For a total of three applications (EP-3)	Tomato (*Solanum lycopersicum*)	EP-1 - increase in tomato plant height, stomatal conductance, chlorophyll content, decrease in fruit firmness; EP-3 - significant increase in yield, a higher percentage of fruit cracking, decrease in nutrient (N, Mg) content in leaves; both applications - decrease in the leaf damage index as compared to the control	Chrysargyris *et al.*, 2020

Thyme (*Thymbra capitata*)	Hydrodistillation from dried aerial parts	Pot experiments, seed coating, 40 µL of the coating product and 400 µL of thyme oil/10 g of seeds, continuous rotation	Durum wheat (*Triticum turgidum*)	Increase in root and shoot development, chlorophyll, nitrogen balance index, abscisic acid, anthocyanins and flavonoids content in leaves	Ben-Jabeur *et al.*, 2019
Tansy (*Tanacetum vulgare*), thyme (*Thymus* spp.)	Dried powder mixed with distilled water, 48 h	1% *w/v*, open field, spray	Zucchini (*Cucurbita pepo*)	Higher fruit yield, number of fruits, fruit weight, length, diameter, a positive effect on plant growth, SPAD unit as compared to control	Beni *et al.*, 2020
B) Plant extracts under abiotic stress					
Plant species	**Extraction method**	**Method of application**	**Tested cultivars**	**Effects on crops**	**Reference**
Sorghum, brassica, sunflower	Soaking in distilled water (1 kg/10 L), 24 h, filtration (muslin cloth)	Pot experiments (glasshouse), foliar application, 3%, heat and drought stresses	Wheat (*triticum aestivum*)	Improved wheat performance, grain yield, water-use efficiency and transpiration, better stay-green character, accumulation of more soluble phenolics, stable grain weight and grain number	Farooq *et al.*, 2017
Licorice root (*Glycyrrhiza glabra*)	Dried root, soaking in distilled water (100 g/20 L), 50°C, 24 h, filtration, dilution with water to final volume	Field trials, 0.5%, saline soil contaminated with heavy metals: Cd, Cu, Pb, Ni	Pepper (*Capsicum annuum*)	Increased plant growth and yield, concentrations of photosynthetic pigments, free proline, total soluble sugars, N, P, and K^+, ratio of K^+/Na^+, activities of catalase, peroxidase, ascorbate peroxidase, superoxide dismutase and glutathione reductase; reduced contaminants; Na, Cd, Cu, Pb and Ni concentrations in leaves and fruits	Desoky *et al.*, 2019a
Licorice root (*Glycyrrhiza glabra*)	Root was dried and soaked in water (100 g/20 L), 50°C, 24 h, filtration, final volume to 20 L with distilled water	Field, seed soaking, foliar spray, 0.5%, salt stress	Common bean (*Phaseolus vulgaris*)	Preliminary study - increased plant growth, yield, relative water content, chlorophylls content; field study - increased growth and yield parameters, photosynthetic pigments, free proline, total soluble carbohydrates, total soluble sugars, nutrients, and selenium, ratio of K^+/Na^+, relative water content, membrane stability index, activities of enzymatic antioxidants, anatomical features; decreased electrolyte leakage, MDA, Na^+, hydrogen peroxide, superoxide radical	Rady *et al.*, 2019
Licorice root (*Glycyrrhiza glabra*)	Root air-dried, immersed in water (5 g/1 L), 50°C, 24 h, filtration, final volume to 20 L with distilled water	Pot experiments (glasshouse), seed soaking, 0.5%, salt stress	Pea (*Pisum sativum*)	Enhanced seedling growth, photosynthetic attributes (chlorophylls, carotenoids, F_v/F_m), ascorbate and glutathione and their redox states, proline, soluble sugars, α-TOC, and enzyme activities; upregulated transcript levels of CAT-, SOD-, APX-, GR-, DHAR-, and PrxQ- encoding genes; decreased oxidative stress and Na^+ and Cl^- contents and increased K^+ content and K^+/Na^+ ratio	Desoky *et al.*, 2019b
Moringa seed (*Moringa oleifera*)	Air-dried ground, stirring with 80% ethanol, (200 g/2 L), shaker, 5 h, filtration, solvent evaporation, dilution with water to final volume	Field trials, spray, 0.5%, saline soil contaminated with heavy metals: Cd, Cu, Pb, Ni	Pepper (*Capsicum annuum*)	Increased plant growth and yield, leaf contents of leaf photosynthetic pigments, free proline, total soluble sugars, N, P, and K^+, ratio of K^+/Na^+, and activities of CAT, POX, APX, SOD and GR; reduced contaminants; Na^+, Cd, Cu, Pb and Ni contents in plant leaves and fruits	Desoky *et al.*, 2018a
Moringa fresh leaf (*Moringa oleifera*), sorghum leaves	Moringa: grinding fresh moringa leaves (kept in freezer overnight) with water (10 kg/L), filtration; sorghum: soaking of dry biomass for 24 h in distilled water (1:10, *w/v*), filtration	Pot experiments, foliar spray, 3%, heat stress	Quinoa (*Chenopodium quinoa*)	Averted the terminal heat stress induced changes on the photosynthetic pigments and gas exchange attributes; declined concentration of leaf H_2O_2 and MDA; improved activity of antioxidants: catalase, peroxidase and dismutase; improved seed yield and seed nutritional quality	Rashid *et al.*, 2020
Aloe leaf (*Aloe vera*)	Cold pressing of aloe leaves using a stainless steel drums, filtration of extracted solution gel	Field trials, foliar spray, 10, 20 and 40 mL/L, sand soil conditions	Sage (*Salvia officinalis*)	Increased plant height, number of leaves, number of branches, yield and essential oil percentage, enhanced the leaf anatomical structure	Abbas *et al.*, 2016
Moringa fresh/dry leaf and flower (*Moringa oleifera*)	Grinding fresh moringa leaves with water (10 kg/1 L), filtration, centrifugation	Pot experiments, seed priming, medium supplementation, foliar spray, 3% fresh leaf extract, 10% dry leaf extract, 10% flower extract, heat stress	Maize (*Zea mays*)	Improved heat tolerance, the accumulation of vitamins and antioxidants, the production of ROS and minimised the membrane peroxidation	Batool *et al.*, 2016
Moringa leaves (*Moringa oleifera*)	Young leaves mixed with 80% ethanol (200 g/2.25 L), stirring using a homogenizer, filtration	Pot experiments (open glasshouse), foliar spray, 3%, salt stress	Sudan grass (*Sorghum vulgare* var. *sudanense*)	Increased growth characteristics, photochemical activity, content of RNA, DNA, phytohormones, osmoprotectants and non-enzymatic antioxidants and activities of antioxidant enzymes	Desoky *et al.*, 2018b
Moringa leaves (*Moringa oleifera*)	Fresh leaves frozen overnight and pressed, filtration, centrifugation	Field experiments, foliar spray, 3%, deficit irrigation	Squash (*Cucurbita pepo*)	Increased growth and yield, harvest index, water use efficiency, chlorophyll fluorescence, photosynthetic pigments, soluble sugars and free proline, leaf anatomy, relative water content and membrane stability index; lowered electrolyte leakage	Abd El-Mageed *et al.*, 2017
Moringa fresh leaves (*Moringa oleifera*)	Fresh leaves rinsed with water, kept in freezer overnight, mechanical extraction, filtration	Pot experiments (wire house), foliar spray, 3%, thermal heat stress	Quinoa (*Chenopodium quinoa*)	Mitigated adverse effects of heat stress; increased photosynthetic rate, intrinsic water use efficiency; improved leaf chlorophyll and antioxidants; increased seed yield under normal and heat stress conditions	Rashid *et al.*, 2018

Moringa leaves (*Moringa oleifera, M. peregrena*)	Extraction with water (200 g/500 mL), filtration (muslin cloth), centrifugation	Pot experiments (glasshouse), irrigation, 2.5, 5, 10, 20%, salt stress	Sweet basil (*Ocimum basilicum*)	Decreased proline and MDA; enlarged leaf area; increased shoot length, shoot fresh weight, shoot dry weight, number of branches, root length, root dry weight, anthocyanin, total carbohydrates and superoxide dismutase, ascorbic acid oxidase	Hassanein *et al.*, 2019
Sugar beet (*Beta vulgaris*)	Fresh sugar beet roots washed, , juice extracted using an electric extractor, filtration	Germination and pot experiments (natural environmental conditions), seed priming/soaking (12 h), 10, 20, 30, 40 and 50%, water stress	Wheat (*Triticum aestivum*)	Ameliorated germination attributes (time to 50% emergence, germination index, mean emergence time, germination percentage, coefficient of uniformity of emergence, germination energy); improved plant growth, photosynthetic pigments, antioxidants' activities and nutrient homeostasis	Noman *et al.*, 2018
Palm pollen grains (*Phoenix dactylifera*)	Pollen grain powder mixed with ethanol (10 g/100 mL), 72 h, occasional stirring, filtration, solvent evaporation	Pot experiments (open glasshouse), foliar spray, 1 g/L, drought stress	Sweet basil (*Ocimum basilicum*)	Improved growth characteristics and the content of essential oil, soluble sugars, free proline, ascorbic acid, leaf photosynthetic pigments, antioxidant enzyme activities, relative water content, water use efficiency, anatomical characteristics; diminished electrolyte leakage	Taha *et al.*, 2020
Alfalfa plant (*Medicago sativa*)	Enzymatic hydrolysis	Pot experiments (aerated complete culture solution; climate chamber), supplement to the culture solution (48 h), 1 mg/L, salt stress	Maize (*Zea mays*)	Stimulation of the growth and N assimilation; increased biomass, gene expression and decreased the activity of antioxidant enzymes and the synthesis of phenolics; induced the activity of enzymes functioning in N metabolism; enhanced flavonoids content	Ertani *et al.*, 2013
Cuscuta reflexa growing parasitically on *Ziziphus mauritiana*	Fresh biomass washed and cut into small pieces, homogenization with electric blender, screw pressing, filtration	Pot experiments, natural environmental conditions, seed priming, 10, 20, 30, 40, 50%, water stress	Wheat (*Triticum aestivum*)	Ameliorated the adverse effects of water stress on seed germination attributes and activities of germination enzymes; improved growth and yield - associated with an improvement in water relations, photosynthetic pigments, nutrient acquisition, reduced lipid peroxidation, better antioxidative defence mechanisms	Ali *et al.*, 2020
Foeniculum vulgare seeds, *Ammi visnaga* seeds	Seeds, air-dried, room temp., ground into a fine powder, immersion of powder in distilled water, 72 h, the residue was discarded, lyophilization	Pot experiments, open greenhouse, foliar spray, *F. vulgare* seed extract (2000 mg/L) and *A. visnaga* seed extract (2000 mg/L), salinity	Cowpea (*Vigna unguiculata*)	Increased the content of osmoprotectants and activities of antioxidant system ingredients, reduced Na^+ content, electrolyte leakage, oxidative stress biomarkers; increased growth and yield traits, leafy relative content of water, membrane stability index, photosynthetic efficiency, nutrient contents, K^+/Na^+ ratio, anatomical features	Desoky *et al.*, 2020
Maize grain	Maize grains covered under wetted cotton until were mushy, grounding with distilled water, filtration; residues on the filter paper were extracted with ethyl alcohol (95%), 72 h, filtration, solvent evaporation; mixing the aqueous and alcoholic extracts	Pot experiments (a glasshouse), seed priming, 1, 2 and 3%, cadmium stress	Wheat (*Triticum aestivum*)	Elevated the biomass and grain outputs; improved photosynthetic efficiency, non-enzymatic and enzymatic antioxidant activities, osmoprotectants, polyamines, and plant hormones contents, ascorbic acid and glutathione reducing power activity; restricted the accumulation of cd ion in roots, leaves and grains; activated the antioxidant defences under Cd stress	Alzahrani and Rady, 2019

C) Plant extracts under biotic stress

Plant species	Extraction method	Method of application and pest	Tested cultivars	Effects on crops	Reference
Insecticide					
Tephrosia Vogel's (*Tephrosia vogelii*), white tephrosia (*Tephrosia candida*)	Soaking of powder of air-dried and milled leaves in cold water (10, 40 and 100 g/2 L), room temp., filtration	Field, spray, 0.5, 2, 5% (*w/v*), insect pest - bean aphid (*Aphis fabae*)	Common bean (*Phaseolus vulgaris*)	Reduced aphid population per plant, pod length, and bean yield; increased pod length and bean yield, mortality rate of aphid on the plots	Kayange *et al.*, 2019
Tephrosia Vogel's (*Tephrosia vogelii*), moringa (*Moringa oleifera*)	Extraction of air-dried biomass with water (500 g/L), soaking, 24 h, filtration (muslin cloth)	Field, spray, 5, 10, 20% (*v/v*), insect pests - flea beetle (*Phyllotreta cruciferae*), melon fruit fly (*Dacus cucurbitae*), spotted cucumber beetle (*Diabrotica undecimpunctata*)	Watermelon (*Citrullus lanatus*)	Protected against the insects	Alao and Adebayo, 2015
Sweet orange (*Citrus sinensis*), tree-gamhar (*Gmelina arborea*), chilli pepper (*Capsicum annum*), African basil (*Ocimum gratissimum*), Lemon eucalyptus (*Eucalyptus citriodora*)	Extraction of dried under shade biomass with hot water (500 g/3.5 L, for chilli pepper - 100 g), 70°C, stirring, left overnight, filtration (muslin cloth)	Field, spray, lima bean pod borer (*Maruca vitrata*), African pod bug (*Clavigralla tomentosicollis*)	Cowpea (*Vigna unguiculata*)	Effectively reduced the incidences of *M. vitrata* and *C. tomentosicollis* on flowers and pods; increased grain yield	Oparaeke, 2007

Goat weed (*Ageratum conyzoides*), physic nut (*Jatropha curcas*), siam weed (*Chromolaena odorata*), bitter leaf (*Vernonia amygdalina*), sweetsop (*Annona squamosa*)	Shade-dried biomass, in the form of powder was extracted with warm water (450 g/3.5 L), 60°C, stirring for 10 min, left for12 h, filtration (muslin cloth)	Field, spray, flea beetles (*Podagrica uniforma*, *P. sjostedti*)	Okra (*Abelmoschus esculentus*)	*Jatropha curcas*, *Vernonia amygdalina* and *Annona squamosa* significantly reduced the population of the two flea beetles; *Ageratum conyzoides* and *Chromolaena odorata* reduced the population of the pests but not significantly	Onunkun, 2012
Asteraceae species: *Vernonia amygdalina*, *Tithonia diversifolia*, *Bidens pilosa*; Fabaceae species: tephrosia Vogel's (*Tephrosia vogelii*), Verbenaceae species: *Lippia javanica*, *Lantana camara*	Plant powder mixed with water (1 kg/10 L), ambient temp. (20±5°C), 24 h, filtration	Field, 10%, pest species (aphids, flower beetles and foliage beetles)	Bean (*Phaseolus vulgaris*), pigeon pea (*Cajanus cajan*), cowpea (*Vigna unguiculata*)	*Bidens pilosa*, *Lantana camara*, *Lippia javanica*, *Tephrosia vogelii*, *Tithonia diversifolia*, and *Vernonia amygdalina* resulted in crop yields comparable to the use of a synthetic pesticide	Tembo *et al*., 2018
Asteraceae species: *Tithonia diversifolia*, *Vernonia amygdalina*, Fabaceae species: *Tephrosia vogelii*, Verbenaceae species: *Lippia javanica*	Plant powder mixed with water, ambient temp. (20±5°C), 24 h, filtration	Field trials, 1 and 10%, spray, aphids (*Aphis fabae*), bean foliage beetle (*Ootheca* mutabilis, *O. bennigseni*), flower beetle (*Epicauta albovittata*, *E. limbatipennis*)	Common bean (*Phaseolus vulgaris*)	Effective control of key pest species that was comparable to the pyrethroid synthetic	Mkenda *et al*., 2015
Moringa leaf, neem seed	Fresh moringa leaves, blending in water (10 kg/L), filtration (muslin cloth), centrifugation; ground neem seeds soaked in water (100 g/L), 3-7 days	Field trials, Spray, neem - 5%, moringa - 3%, aphid species: *sitobion avenae*, *Schizaphis graminum*, *Rhopalosiphum padi*	Wheat (*Triticum aestivum*)	Suppressed aphid population	Shah *et al*., 2017
Lamiaceae species: *Clerodendrum viscosum*	100 g, 500 g, 1 kg and 2 kg of dry biomass in 10 L of distilled water, shaking (mechanical shaker), 8 h, kept in the water for 24 h, filtration	Field trials, 1, 5, 10, 20%, spray, tea mosquito bug (*Helopeltis theivora*), the tea red spider mite (*Oligonychus coffeae*)	Tea (*Camellia sinensis*)	Effectively and significantly reduced the mite population as well as infestation of tea mosquito bug, and their bioefficacy was comparable to synthetic and neem pesticides	Roy *et al*., 2010
Neem (*Azadirachta indica*), tree - Fabaceae family (*Milletia ferruginea*)	Biomass powder mixed with water (5 kg/100 L), 24 h, filtration	Field trials, 5%, spray, cotton bollworm (*Helicoverpa armigera*)	Chickpea	Effective in reducing per plant *H. armigera* larval populations, pod damage with increased the subsequent yields	Fite *et al*., 2020
Neem (*Azadirachta indica*)	Freeze-dried and macerated in a mortar biomass, 96% ethanol (1 g/20 mL), mixture kept in the dark, 25±1°C and shaken at 120 rpm, 24 h, filtration, again extraction of the biomass (3 times), solvent evaporation	Field trials, 150 mL of formulation (extract, water, castor oil, Tween 80), fall armyworm (*Spodoptera frugiperda*)	Corn	Provided field-level insect protection	Zuleta-Castro *et al*., 2017
Fumaria parviflora (Fumariaceae), *Teucrium polium* (Lamiaceae), *Calotropis procera* (Asclepiadaceae), *Thymus vulgaris* (Lamiaceae)	Biomass, air-dried 4-5 days, ground extraction with ethanol (20 g/90 mL) and water (20 g/210 mL), 12 h	Pot experiments (glasshouse), leaves dipping (5 s), sweet potato whitefly (*Bemisia tabaci*)	Tomato	Fumitory had a noticeable effect on the different life stages of the sweet potato whitefly	Jafarbeigi *et al*., 2012
Fungicide					
Medicinal plant species: basil leaves (*Ocinum bacilicum*), chilli fruits (*Capsicum frutescens*), eucalyptus leaves (*Eucalyptus globulus*), garlic bulbs (*Allium sativum*), lemon grass leaves (*Cymbopogon citratus*), marjoram leaves (*Majorana hortensis*), onion seeds (*Allium cepa*), peppermint leaves (*Mentha piperita*)	Sun-dried biomass mixed with distilled water (1:10, *w/v*), extraction under cold conditions, 24 h, filtration	Field trial, 2.5, 5 and 10%, spray, late blight (*Phytophthora infestans*), early blight (*Alternaria solani*)	Potato (*Solanum tuborsum*)	Reduced mycelial growth and inhibited spore germination of both fungal species	Abd-El-Khair and Haggag, 2007
Garlic (*Allium sativum*)	Fresh biomass homogenized in distilled water (8 g/100 mL), centrifugation, filtration	Pot trials, 20, 40 and 60 mg/mL, spray, leaf mold (*Fulvia fulva*)	Tomato (*Solanum lycopersicum*)	Effectively controlled the leaf mold in tomato caused by *F. fulva*	Wei *et al*., 2011
Garlic (*Allium sativum*)	Ground garlic diluted in distilled water (10 g/100 mL)	Pot trials, 37.5, 50, 75, 100, 150 mg/mL, pepper blight (*Phytophthora capsici*)	Sweet pepper (*Capsicum annuum*), chili pepper	Inhibited the mycelial growth of *P. capsici*	Li and Zhihui, 2009

Garlic (*Allium sativum*)	Extraction of juice from garlic using a domestic juicer, centrifugation, filtration	Pot trials, 5 mL/pot, spray, cucumber downy mildew (*Pseudoperonospora cubensis*), Phytophthora blight (*Phytophthora infestans*)	Cucumber (*Cucumis sativus*) and tomato	Inhibited the germination of sporangia and cysts and subsequent germ tube growth by *Phytophthora infestans* on the leaf surface	Portz *et al*., 2008
Garlic (*Allium sativum*)	Fresh garlic ground in a mortar and pistil, homogenized in distilled water (10 g/100 mL), centrifugation, filtration	Glasshouse pot trial, spray, 50, 150, 300 mg/mL, fungi: *Botrytis cinerea*, *Fusarium oxysporum*, *Verticillium dahliae*, *Phytophthora capsici*	Cucumber (*Cucumis sativus*)	Biologically active inside cucumber seedlings and alters the defence mechanism of the plant	Hayat *et al*., 2016
Garlic (*Allium sativum*)	Garlic bulbs crushed in a mortar and pistil, homogenization with distilled water (10 g/100 mL), centrifugation, filtration	Pot experiments (a glasshouse), foliar spray, fertigation, 100 µg/mL, *Phytopthora capsica*	Eggplant (*Solanum melongena*) and pepper (*Capsicum*)	Improved plant height, number of leaves, root growth, fresh and dry weight; indicated alterations in metabolites (chlorophyll, carotenoids, soluble sugars); stimulated antioxidant enzymes (superoxide dismutase, peroxidase), root activity; induced defence responses prior to *Phytopthora capsica* inoculation	Hayat *et al*., 2018
Amazon cinnamon leaves (*Ocotea quixos*), pepper (*Piper carpunya*)	Extraction via maceration and herbal distillation	Field, spray, 40, 60%, *Fusarium* sp., *Capnodium* sp.	Red ginger (*Alpinia purpurata*), heliconia (*Heliconia wagneriana*)	Showed an inhibitory activity against *Fusarium* sp. and *Capnodium* sp., biostimulating effect on flower spikes	Cárdenas *et al*., 2018
Horsetail (*Equisetum arvense*)	Powder biomass added to water (600 g/10 L), fermentation (maceration), room temp., 7 days, filtration	Field trials, foliar sprays, 1:5, oomycota: *Phytophthora infestans* (late blight), fungi: *Puccinia triticina* (brown rust), *Fusarium graminearum*, *Zymoseptoria tritici*	Tomato (*Solanum lycopersicum*), durum (*Triticum turgidum*)	For tomato - significantly reduced the late blight and increased yield in tomato; for durum wheat - significantly reduced brown rust infection and increased yield under moderate infection, unsuccessful under unfavourable meteorological conditions resulting in the combined and severe spread of *P. triticina*, *F. graminearum* and *Z. tritici*	Trebbi *et al*., 2021
Great ragweed (*Ambrosia trifida*), false indigo bush (*Amorpha fruticosa*), american pokeweed (*Phytolacca americana*), black locust (*Robinia pseudoacacia*)	Plants, air-dried, chopped into small pieces, extraction 3 times with 80% methanol, overnight, room temp., solvent evaporation, sample freeze-drying, 12 h	Pot experiments (a glasshouse), spray, 30,000 mg/L, rice blast (*Magnaporthe oryzae*), rice sheath blight (*Rhizoctonia solani*), tomato gray mold (*Botrytis cinerea*), tomato late blight (*Phytophthora infestans*), wheat leaf rust (*Puccinia recondita*), barley powdery mildew (*Blumeria graminis* f. sp. *hordei*), pepper anthracnose (*Colletotrichum coccodes*)	Rice (*Oryza sativa*), tomato (*Lycopersicon esculentum*), barley (*Hordeum sativum*), wheat (*Triticum asetivum*), pepper (*Capsicum annuum*)	*Phytolacca americana* effectively suppressed rice blast, tomato gray mold, and tomato late blight. *Amorpha fruticosa* exhibited potent antifungal activity against pepper anthracnose	Bajpai *et al*., 2012
Sweat basil (*Ocimum basilicum*), neem (*Azadirachta indica*), eucalyptus (*Eucalyptus chamadulonsis*), jimsonweed (*Datura stramonium*), oleander (*Nerium oleander*), garlic (*Allium sativum*)	Fresh leaf material, washed with water, crushed in a mortar with pestle with distilled water (1 g/10 mL), centrifugation of homogenate	Pot experiments (glasshouse), foliar application, 1 and 5%, the early blight disease (*Alternaria solani*)	Tomato (*Solanum lycopericum*)	Significantly reduced the early blight disease, increased the yield of tomato	Nashwa and Abo-Elyou, 2012
Herbicide					
Sorghum (*Sorghum bicolor*)	Chaffed sorghum, soaking in water (1:20, *w/v*), 24 h, filtration	Pot culture, spray, 25 mL/pot	Weed of cereals - purple nutsedge (*Cyperus rotundus*)	Reduced the purple nutsedge population	Cheema *et al*., 2009
Sorghum (*Sorghum bicolor*)	Chaffed sorghum, soaking in water (1:20, *w/v*), 24 h, filtration	Field trial, spray, 5 and 10%, 30 and 60 days, weeds (*Fumaria indica*, *Phalaris minor*, *Rumex dentatus*, *Chenopodium album*)	Controlling weeds of wheat (*Triticum aestivum*)	Controlled weeds, increased wheat yield	Cheema and Khaliq, 2000
Teak (*Tectona grandis*)	Powdered teak leaves, extraction in Soxhlet apparatus, methanol, (2 kg/2 L), three batches, 6 h, solvent evaporation	Field trial, spray, weeds (*Echinochloa colona*, *Echinochloa crus-galli*)	Wheat	Reduced weed population	Kole *et al*., 2016
Basil (*Ocimum basilicum*)	Extraction of fresh biomass with methanol, acetone, deionized water (4 kg/2 L), 72 h, filtration, solvent evaporation	Pot trial, spray, 1 and 2%, *Amaranthus* sp. and *Portulaca* sp. weeds	Maize and soybean	Reduced the fresh weight of *Amaranthus* sp. and *Portulaca* sp. weeds	Mekky *et al*., 2019

Lemon eucalyptus (*Eucalyptus citriodora*), basil (*Ocimum basilicum*), mentha (*Mentha arvensis*)	Extraction of essential oils from leaves, hydro-distillation (Clevenger's apparatus), drying	Pot trial/greenhouse, spray, formulations with Tween 80, 50, 75, 100 µL/mL, *Angallis arvensis*, *Cyperus rotundus*, *Cynodon dactylon*	–	Reduced the weed growth, root and shoot length	Khare *et al.*, 2019
Cardoon (*Cynara cardunculus*)	Powder, stirring in methanol (10 g/100 mL), 30 min, solvent evaporation, dry residues re-dissolution in 1% Tween, 4°C, 24 h, filtration	Greenhouse, pure phenolic compounds: querectin - 250 µg/mL, naringenin - 90 µg/mL, myricitrin - 60 µg/mL, spray, weeds (*Trifolium incarnatum*)	–	Inhibited weed germination and seedling growth, and caused necrosis or chlorosis	Kaab *et al.*, 2020

nolics, ascorbic acid, tocopherols, selenium, glutathione, free proline, soluble sugars; phytohormones such as auxins, gibberellins, zeatin-type cytokinin; micro- (Cu, Fe, Mn, Zn) and macroelements (Ca, Mg, N, P, K, S) (Hussain *et al*., 2013; Jabran and Farooq, 2013; Farooq *et al*., 2017; Desoky *et al*., 2018a, 2018b, 2019a, 2019b). The presence of auxins, cytokinins, gibberellins, and abscisic acid and their metabolites was also confirmed by Basra and Lovatt (2016) in young fully expanded moringa leaves.

The extract produced from *Aloe vera* is used as a biostimulant of plant growth due to the rich chemical composition - essential and non-essential amino acids, saccharides (glucose, mannose, cellulose), micro- (Cu, Fe, Mn, Zn) and macroelements (Ca, K, Mg, N, P), vitamins (*e.g*., B_1, B_2, B_6, C), phytohormones (*e.g*., gibberellins, salicylic acid) and compounds typical to aloe such as aloin (Abbas *et al*., 2016).

Extracts obtained from licorice root enhance plant performance due to the content of antioxidants and osmoprotectants such as vitamins: α-tocopherol, ascorbic acid, vitamins from A, and B group, glutathione, salicylic acid, selenium, amino acids, proline, and soluble sugars. This extract is also a rich source of phytohormones such as auxins, gibberellins, cytokinins (zeatin-type), and nutrients (Desoky *et al*., 2019a).

Several natural plant extracts contain active compounds, which may enhance the plant performance under stress conditions, *e.g*., heat and drought stresses (Farooq *et al*., 2017). For example, extract from sorghum contains ferulic, *p*-coumaric, *p*-hydroxybenzoic, syringic, and vanillic acid (Cheema, *et al*., 2009; Jabran and Farooq, 2013; Farooq *et al*., 2017), sunflower extract is composed of caffeic, chlorogenic, ferulic, syringic and vanillic acids (Jabran and Farooq, 2013; Farooq *et al*., 2017). Glucosinolates - biologically active compounds are found in extracts produced from plants belonging to *Brassicaceae* family, *e.g*., brassica. Other compounds in this extract are plant hormones - brassinosteroids such as 28-homobrassinolide, which protect plants exposed to the various abiotic stress or brassinolides - plant growth regulator (Jabran and Farooq, 2013; Farooq *et al*., 2017).

Plant extracts, due to their composition and activity can also increase plant resistance to biotic stress. Garlic is a very popular extract with stimulating and antifungal properties. This extract is known to be highly nutritive due to a large number of biochemical compounds - more than 200 - such as antioxidants and vitamins (Mohamed *et al*., 2020). Organosulfur compounds such as allicin, diallyl disulfide (DADS) and diallyl trisulfide (DATS) are strong antioxidants (Ali *et al*., 2019). Antifungal, antibacterial and antiviral properties of garlic extracts are also derived from these compounds (Portz *et al*., 2008; Li and Zhihui, 2009).

Compounds known as limonoids are produced by neem (*Azadirachta indica*). They have an antifeedant activity against a large number of insect species (Zuleta-Castro *et al*., 2017). Shah *et al*. (2017) showed that seeds of neem trees are rich in extractable highly oxidised limonoids like azadirachtin. An interesting group of plants with anti-insect properties are common weeds. One of them is *Tephrosia vogelii*, the water extract which contains rotenoids (flavonoids) such as deguelin, tephrosin and rotenone, known to be strongly toxic to insects (Mkenda *et al*., 2015). Another one is *Tithonia diversifolia*, which contains sesquiterpene lactones tagitinin A and tagitinin C with anti-insect properties (Mkenda *et al*., 2015; Green *et al*., 2017). Anti-insect properties of *Vernonia amygdalina* were attributed to vernodalin, 11,13-dihydrovernodalin, as well as several vernonioside (Green *et al*., 2017). *Bidens pilosa* belonging to the same *Asteraceae* family as *T. diversifolia* and *V. amygdalina* contains bioactive constituents such as β-caryophyllene and τ-cadinene (Deba *et al.*, 2008). *Lippia javanica* extracts can be used as bioinsecticides due to the content of α-pinene, camphor, camphene, 2-carene, caryophyllene α-cubebene, cymene, eucalyptol, linalool, thymol, *Z* and *E* α-terpineol (Mkenda *et al.*, 2015).

Some plants show the activity attributed to herbicides. For example, methanol extract from teak (*Tectona grandis*) contains phenolic acids (benzoic, caffeic, gallic, salicylic, tannic, and vanillic acid), which are the major allelochemicals responsible for the inhibition of plants (weeds) germination (Kole *et al.*, 2016). Also, Kaab *et al.* (2020) found that methanolic extract from cardoon (*Cynara cardunculus*) has in its composition phenolic compounds, such as myricitrin, naringenin, quercetin, *p*-coumaric acid and syringic acid, which inhibited the germination of weeds, seedling growth and caused chlorosis or necrosis. Another natural weed inhibitor can be sorghum extract, which provides soluble allelochemicals being phytotoxic to certain weeds (Cheema and Khaliq, 2000). *Ocimum basilicum* extract can also be applied as a biodegradable herbicide due to the content of allelochemicals. Mekky *et al.* (2019) pointed to the richness of the chemical composition of the basil extract, which contained 2-cyclopenten-1-one, 2,5,5-trimethyl, 3-cyano-5,5-dimethyltetrafuran-2-one, linoleic acid, methyl ester, 9,12-octadecadienoic acid (*Z,Z*), phthalic acid, di(2-propylpentyl) ester, 1,2-benzenedicarboxylic acid, 6-octadecenoic acid, methyl ester, (*Z*), 2,3-bis(acetyloxy) propyl laurate, squalene, thymol, 2-cyclohexen-1-one, 4-(3-hydroxy-1-butenyl)-3,5,5-trim ethyl, hexadecenoic acid, methyl ester, cis-linalool oxide. Khare *et al.* (2019) showed that essential oils (EOs) extracted from Lemon eucalyptus (*Eucalyptus citriodora*), basil (*O. basilicum*), field mint (*Mentha arvensis*) demonstrated the phytotoxicity on weeds. The major constituent in essential oils extracted from *E. citriodora* was citronellal, well known for its allelopathic effect and additionally isopulegol and citronellol. *Ocimum* essential oils were methyl chavicol, linalool and geranial and menthol, menthone, iso-methanone were the major constituent of the mentha essential oils. The application of plant extracts could reduce the use of chemical herbicides and bring economic benefits (Cheema and Khaliq, 2000).

Effect of plant-based biostimulants on plant growth, development and quality

Plant-derived biostimulants enhance plant growth, quality, photosynthesis, tolerance to abiotic and biotic stresses, and the resources use efficiency (nutrients, fertilisers, and water) by modulating plant biochemical, molecular, and physiological processes (Bulgari *et al.*, 2015; Ertani *et al.*, 2015; Yakhin *et al.*, 2017; Rouphael and Colla, 2018; Zulfiqar *et al.*, 2019; Dipak Kumar and Aloke, 2020; Rouphael and Colla, 2020). The examples of the positive effects of PDBs on crop plants are presented in Table 1. To improve the biostimulants efficacy and to optimise the industrial processes, understanding their mode/mechanism of action should be improved (Brown and Saa, 2015). However, the mechanisms triggered by biostimulants are difficult to define (Yakhin *et al.*, 2017; Di Mola *et al.*, 2019) mainly due to the diversity of raw materials and the complexity of the resulting product (Brown and Saa, 2015). These bio-products are a rich source of bioactive compounds, active at low dosages that are easily absorbed by plants (Ertani *et al.*, 2016; Di Mola *et al.*, 2019; Dipak Kumar and Aloke, 2020). The final effect of their application depends on the crop species, cultivar, development stage, environmental conditions, and also dose, time, and method of PDBs application (Ertani *et al.*, 2016; Di Mola *et al.*, 2019). European agricultural and food safety policies encourage more environmentally friendly and safe agricultural practices in response to consumer expectations for healthy food (Bulgari *et al.*, 2015; Ertani *et al.*, 2016). Initially, biostimulants were used in organic farming or restricted to higher-value fruit and vegetable markets, but today they are also adopted in conventional and integrated systems (Rouphael and Colla, 2020). The growing interest in PDBs is observed among scientists, specialists, private industry, and growers (Rouphael and Colla, 2018). These natural products are increasingly integrated into the high value of fruit, vegetable, and floriculture production systems worldwide (Brown and Saa, 2015; Zulfiqar *et al.*, 2019) as a safer agricultural practice for increasing crop quantity and quality while reducing environmental contamination (Ertani *et al.*, 2016). Europe is the largest PDBs market (34%), followed by the North American (23%) and Asian-Pacific (22%) of the worldwide market share (Rouphael and Colla, 2018). The global market of natural biostimulants is expected to grow by 11.2% from 2019 to reach almost $5 billion by 2025 (Rouphael and Colla, 2018, 2020; Dipak Kumar and Aloke, 2020).

One of the most widely used higher plants for the production of potential biostimulants is moringa (*Moringa oleifera*) (Table 1). The impact of its extracts has been tested on many crops, *e.g.*, cherry tomato (Basra and Lovatt, 2016), coriander (Mazrou, 2019), plum trees (Thanaa *et al.*, 2017), wheat (Khan *et al.*, 2017), pea plants (Merwad, 2018), and rocket (Mona, 2013). All researchers confirmed the positive effects of their use and observed the increase of yield, the content of photosynthetic pigments, oils, elements, proteins, total sugars, phenols, ascorbic acid, anthocyanins, growth-promoting hormones, as well as antioxidant activity contents.

Legumes are often used as raw material for the production of biostimulants of plant growth. Pretorius (2007) investigated extracts obtained from seeds of the species *Lupinus albus*, which showed significant bio-stimulatory activity on coleoptile and root growth both under field and glasshouse conditions. Also, the author assessed the effects of combined extracts from seeds of *L. albus* with extracts of seeds or plant parts of species of the *Pink* family and *Alfalfa* species (known as the commercially available product designated as ComCat®) showing a higher bio-stimulatory efficacy as compared to the extracts or preparations of the single species, and suggests that synergism has participated in the involved biological processes. Another study regarding alfalfa was carried out by Ertani *et al.* (2017), who obtained a protein hydrolysate that was assessed as a biostimulant in tomato (*Solanum lycopersicon*). The obtained biostimulant (used at 1 mL/L) promoted the fresh biomass and the content of chlorophyll and soluble sugars in tomato plants. This effect on plant productivity was due to the up-regulation of genes involved in primary carbon and nitrogen metabolism, photosynthesis, nutrient uptake, and developmental processes. Also, the extract up-regulated several genes implied in the secondary metabolism that leads to the synthesis of phenols and terpenes. Parrado *et al.* (2008) reported the biological process to convert carob (*Ceratonia siliqua*) germ into a water-soluble enzymatic hydrolysate extract. The main component of the extract was protein (68%), in the form of peptides and free amino acids. The obtained extract had a significant biostimulant effect on tomato plants (*Lycopersicon pimpinellifolium* cv. Momotaro). In particular, plant height, the number of flowers per plant, and number of fruits per plant were increased using the carob extract. Apone *et al.* (2010) described the preparation of a new mixture of peptides and sugars derived from the chemical and enzymatic digestion of *Nicotiana tabacum* cv. BY-2 cell wall glycoproteins. The authors investigated the multiple roles of the extracted product as a potential 'biostimulator' to protect plants from abiotic stresses. In particular, the effects of the peptide/sugar mixture induced plant defence, protecting cultured skin cells from oxidative burst damages in *Arabidopsis thaliana* plants. Protein hydrolysate was also produced by Ugolini *et al*. (2015) from sunflower (*Helianthus annuus*) defatted seed meal, which represents an abundant by-product coming from the biodiesel chain oil extraction. The biostimulant properties of the obtained hydrolysate were investigated both in Petri dishes on garden cress (*Lepidium sativum*) and lettuce (*Lactuca sativa*) seedlings and by performing experiments in a pots on maize plants. The sunflower hydrolysate showed auxin-like activity and interesting effects on plant root elongation, suggesting potential use of the product as an effective biostimulant in the agricultural field.

The second most commonly utilised raw material is licorice (*Glycyrrhiza glabra*). The beneficial impact of its application (improved growth, development, and chemical composition) was observed on common bean (Rady *et al*., 2019), onion (Babilie *et al*., 2015), almond (Thanaa *et al*., 2016), and fennel (El-Azim *et al*., 2017).

The literature also showed the favourable influence of foliar spraying with extracts from garlic (*Allium sativum*) in the cultivation of faba bean (increased yield and quality) (Mohamed *et al*., 2020), eggplant (improved growth and development, antioxidant enzymes, photosynthesis) (Ali *et al*., 2019), and snap bean (enhanced growth, leaf and pod chemical compositions) (Elzaawely *et al*., 2018). Ali *et al*. (2019) studied the effect of aqueous garlic (*A. sativum*) bulb extract on the growth and physiology of eggplant grown in a plastic tunnel. Aqueous garlic bulb extract was applied as a foliar spray with three different frequencies (once, twice, and three times) and at two independent growth stages (pre- and post-transplant). The authors showed that the treated plants exhibited positive responses in growth and physiology in accord with the repetition of aqueous garlic bulb extract and growth stage of the plants, respectively. Besides, the post-transplant application also displayed an increased growth. Another study regarding garlic was performed by Hayat *et al*. (2018), who assessed garlic-derived substances as biostimulants, using 100 μg/mL of aqueous extract in consort with 1 mM of acetylsalicylic acid and distilled water as a control. Treatments were applied to eggplant and pepper seedlings as a foliar application and as fertigation. The authors reported positive responses in the growth of the investigated crops with improved plant height, number of leaves, root growth, fresh and dry weight, using aqueous garlic extracts and acetylsalicylic acid applications.

There are also recent scientific reports (Table 1) on the possibility of using other raw materials. For instance, the foliar application of extracts based on, *e.g*., common dandelion (*Taraxacum officinale*), common mugwort (*Artemisia vulgaris*), nettle (*Urtica dioica*), knotgrass (*Polygonum aviculare*), and horsetail (*Equisetum arvense*) exert high biostimulating activity in tests on cabbage seedlings (*Brassica oleracea* var. *capitata*) and can be recommended to enhance the selected tested parameters such as length and weight of shoots and roots as well as the content of photosynthetic pigments (Godlewska *et al*., 2019; Godlewska *et al*., 2020a). Findura *et al*. (2020b) studied the extract from *A. vulgaris* as a biostimulant. The experiment was carried out under controlled environmental conditions on a very early cultivar of potato (cv. Irys). The authors showed that foliar treatment with the obtained extract had a positive effect on the content of chlorophyll *a* and chlorophyll *b* in potato leaves. The highest increase was recorded in plants sprayed using the dose of 0.6 mL per plant. Also, an increase in the carotenoids content was observed in treated plants.

The members of the *Brassicaceae* family can also be used for the production of biostimulants. Sequi *et al*. (2009) proposed a bioassay to test the stimulation effect of a liquid *Brassicaceae* (*Brassica napus* var. *oleifera*) extract on the early stage of plant growth. The study described the dynamics of maize seedlings development in relation to the allocation of resources from seed to shoot and root during the first three days of growth, under controlled conditions. In particular, seedlings treated with biostimulant consumed more slowly the caryopsis reserves, recording higher radicle biomass.

Aromatic plants and medicinal plants rich in essential oils are known to have a wide range of biological activities including biostimulant properties (Souri and Bakhtiarizade, 2019). Among them, the most popular are rosemary (Souri and Bakhtiarizade, 2019; Chrysargyris *et al*., 2020), eucalyptus (Chrysargyris *et al*., 2020), thyme (Ben-Jabeur *et al*., 2019; Beni *et al*., 2020), tansy (Beni *et al*., 2020). Essential oils extracted from rosemary or eucalyptus contain 1,8-cineole, which is known to possess antibacterial, antifungal, herbicidal, and insecticidal properties (Chrysargyris *et al*., 2020). The oil composition may vary depending on plant organs, genetics, growth conditions, soil composition, harvest stage, root colonisation by microorganisms (Bajpai *et al*., 2011; Nikolova and Berkov, 2018; Karalija *et al*., 2020; Raveau *et al*., 2020). Essential oils contain a mixture of compounds, specific for each plant, which includes, among others: aldehydes, alkaloids, carotenoids, flavonoids, isoflavones, monoterpenes, phenolic acids, and oxygen-containing, and non-oxygenated terpene hydrocarbons (Zanellato *et al*., 2009; Fierascu *et al*., 2020; Ni *et al*., 2021). Essential oils extracted from aromatic plants can be used not only as sprays, fumigants, or granular formulations but also for seeds coating (Benvenuti *et al*., 2017; Beni *et al*., 2020). Ben-Jabeur *et al*. (2019) showed that seed treatment with thyme oils can improve the plant's water and nutrient status and can enhance drought resistance. Some plants like thyme and tansy due to the strong antioxidant properties (high polyphenols content) show not only biostimulant effect on plant growth and fruit production, but can also be used in the integrated crop protection (Beni *et al*., 2020).

Biostimulants of plant growth can also be obtained from flowers. Pretorius (2013) reported extracts based on species of the genus *Agapanthus*, in particular *Agapanthus africanus*, which showed significant bio-stimulatory activity, expressed by an increased growth metabolism. Extracts from the aboveground parts of the *A. africanus* showed a higher efficacy as compared to the belowground parts of the same plant. Furthermore, extracts from the combined use of flowers, leaves, and stalks showed a higher bio-stimulatory efficacy as compared to the sum of extracts or preparations from the single components of the aerial parts of *A. africanus*. Furthermore, combined extracts from species of the genus *Agapanthus* and the species *Tulbaghia violacea* showed a higher bio-stimulatory efficacy as compared to the extracts or preparations of the single species and let assume the existence of a synergistic process. Bulgari *et al*. (2017) exploited raw extracts from leaves or flowers of *Borago officinalis* to enhance the yield and quality of *Lactuca sativa*. Extracts were diluted to 1 or 10 mL/L, sprayed onto lettuce plants at the middle of the growing cycle and 1 day before harvest. Control plants were treated with water. Borage extracts enhanced the primary metabolism by increasing leaf pigments and photosynthetic activity. Plant fresh weight increased upon treatment with 10 mL/L dose. Total flavonoids and phenols, as well as the total protein levels, were increased by all borage extracts. Flower extract also proved efficient in preventing degradation and inducing an increase in photosynthetic pigments during storage.

Moreover, the increment in the root and leaf biomass, chlorophyll, phenol acids, sugars content, and induced phenylalanine ammonia lyase (PAL) activity in maize was observed after the treatment with extracts obtained from red grape skin, blueberry fruits, and hawthorn leaves (Ertani *et al*., 2016). Sánchez-Gómez *et al*. (2017) assessed the non-aromatic vine-shoot extracts as 'viticultural biostimulants' when applied to grapevines. In particular, the authors investigated the application of extracts from non-toasted and toasted vine shoots from the well-known aromatic variety such Moscatel were applied on Airén grapevine leaves, observing an increased grape yield and wines with a lower alcohol degree. Wine phenolic composition was affected positively by extracts from non-toasted vine-shoot in the case of phenolic acids. In order to increase wine polyphenols in grapevines, oak extracts (*Quercus*) can be applied, which was studied by Pardo-García *et al*. (2014). The authors displayed that a mixture of volatiles and non-volatiles phenolics, can act as a plant biostimulant modulating plant physiological responses. In particular, oak extract affected grape composition, producing less alcoholic and acid wines with higher colour intensity, lower shade, and more stable colour and higher content of polyphenols such as gallic acid, acylated anthocyanins, flavanols, and stilbenes.

Additionally, the bio-products based on sugar beet (*Beta vulgaris*) can improve plant growth, photosynthetic pigments, antioxidants' activities, and nutrient homeostasis in wheat (Noman *et al*., 2018), while based on lantana (*Lantana camara*) can increase plant height, number of leaves, dry matter, chlorophyll content, number and weight of pods per plant, number of seeds per pod, and grain yield of green gram (Ganagi and Jagadeesh, 2018). To increase the yield of celeriac (*Apiaceae* family) leaves rosettes and roots, the content of chlorophyll *a* + *b* and carotenoids, the greenness index of leaves, the content of vitamin C in leaves and roots the extracts obtained from St. John's wort (*Hypericum perforatum*), giant goldenrod (*Solidago gigantea*), common dandelion (*Taraxacum officinale*), red clover (*Trifolium pratense*), nettle (*Urtica dioica*), valerian (*Valeriana officinalis*) can be used (Godlewska *et al*., 2020b).

The interest in the use of botanical extracts is expected to grow due to their confirmed beneficial effects on plants. These bio-products can play an important role in the development of sustainable agriculture.

Plant extracts increase tolerance against abiotic stress

Abiotic stress is the most damaging factor affecting the growth, development, quality, and productivity of crops (Mittler, 2006; Bhatnagar-Mathur *et al*., 2008; Cramer *et al*., 2011; Farooq *et al*., 2017; Bulgari *et al*., 2019; Drobek *et al*., 2019; Andreotti, 2020; Malik *et al*., 2020; Teklić *et al*., 2020). Plants elicit a broad range of biochemical, molecular, morphological, and physiological changes (Bhatnagar-Mathur *et al*., 2008; Bulgari *et al*., 2015; Malik *et al*., 2020) that are tailored to the exact environmental conditions (Mittler, 2006). Crops encounter various abiotic stresses like acidity, flooding, pollution, humidity, rain, soil composition (*e.g*., nutrient deficiency, excess of toxic metals), ultraviolet radiation, or wind (Zhu, 2016; Drobek *et al*., 2019; Andreotti, 2020; Saijo and Loo, 2020; Teklić *et al*., 2020), and among the most common can be mentioned: drought, saline soils (constituting approx. 22% of the agricultural land), and temperature extremes (Vinocur and Altman, 2005; Mittler, 2006; Bhatnagar-Mathur *et al*., 2008; Zhu, 2016; Bulgari *et al*., 2019; Malik *et al*., 2020; Teklić *et al*., 2020). The drought stress may generate a decrease of crop yield between 13 and 94%, depending on the intensity and duration of the stress (Bulgari *et al*., 2019). The negative impacts of these environmental conditions can be exacerbated by climate change (Zhu, 2016). How plants sense and respond under unfavourable conditions is overlapping (Vinocur and Altman, 2005). Their reaction involves the modulation of genes associated with signalling and regulatory pathways or genes that encode proteins conferring stress tolerance or enzymes present in pathways leading to the synthesis of functional and structural metabolites (Vinocur and Altman, 2005; Bulgari *et al*., 2019), which result in enhanced amounts of various metabolites and proteins (Vinocur and Altman, 2005; Bhatnagar-Mathur *et al*., 2008). Plants encountering concurrent or sequential stress show different responses in comparison to plants exposed to individual stress. The result of multiple stresses depends on a multitude of factors *e.g*., plant genotypes, stage, and nature, strength and application timing/kinetics of abiotic stress (Malik *et al*., 2020; Saijo and Loo, 2020; Teklić *et al*., 2020). The metabolites play a pivotal role in plant adjustment and survival. The synthesis and activation of numerous compounds involved in carbon-, nitrogen-, sulphur- and minerals' metabolism in plants may be triggered by diverse stress types or their combinations (Teklić *et al*., 2020). Plants grown in the field are constantly exposed to a mixture of diverse abiotic stresses. For instance, in drought-affected areas crops face a combination of drought and other stresses, such as heat or salinity (Mittler, 2006; Andreotti, 2020). The drought and salt stress elicit peculiar signals, for example, hyperosmotic, which induces the accumulation of abscisic acid which trigger numerous adaptive responses in plants (Zhu, 2016). Under heat stress, plants open their stomata to cool their leaves by transpiration, nevertheless, if the heat and drought occur simultaneously, plants are not able to do this and as a result, the leaf temperature is higher. A similar problem may occur under salinity or heavy metal stress combined with heat stress - the increased transpiration might result in higher uptake of salt or heavy metals (Mittler, 2006; Suzuki *et al*., 2014; Sharma *et al*., 2020). Cold or drought stress, coupled with high light conditions, can lead to greater production of reactive oxygen species by the photosynthetic apparatus because these circumstances limit the accessibility of CO_2 for the dark reaction, leaving oxygen as one of the major reductive products of photosynthesis (Mittler, 2006; Suzuki *et al*., 2014; Bulgari *et al*., 2015; Sharma *et al*., 2020). However, knowledge about the molecular mechanisms underlying the adaptation of plants to at least two different stresses is still scarce. This is due to the fact that most of the studies are performed in the laboratory under controlled conditions and do not represent the real growing conditions (Mittler, 2006; Bulgari *et al*., 2019; Andreotti, 2020). This emphasises the significance of field trials conducted for several years in order to consider also the effects of different seasonal conditions (Bulgari *et al*., 2019; Andreotti, 2020). The improvement of plant resistance to abiotic stresses is crucial in crop productivity as well as for environmental sustainability (less water and fertiliser consumption) (Zhu, 2016). Despite the recent significant achievements in genetic transformation, the complex mechanism of abiotic stress tolerance makes the task very difficult (Vinocur and Altman, 2005). The accumulation of compatible solute, reduction in stomatal conductance and the activation of antioxidant systems are essential mechanisms, which support plants better performance under terminal heat and drought stresses (Farooq *et al*., 2017). The most common strategies used to alleviate the adverse impact of abiotic stresses are the choice of proper cultivar, growing period, sowing density, and amount of water and fertilisers, as well as the control of temperatures, radiation, and atmospheric composition. The soilless cultivation, grafting, and genetic improvement can also be applied (Bulgari *et al*., 2019). In addition to these approaches, the improvement of the aforementioned mechanisms can be achieved by the exogenous application of osmoprotectants, stress signalling molecules, and plant extracts can be considered. However, the use of plant extracts seems to be the cheapest eco-friendly alternative (Farooq *et al*., 2017; Desoky *et al*., 2020). It has been shown that bioactive molecules present in plant-based biostimulants can improve the growth and development of crops under stress conditions (Table 1), by acting on the primary or secondary metabolism, mechanisms involving phytohormones and antioxidants, and modulating the phytohormones metabolism, water/nutrient uptake, enzyme function, photosynthesis, gene expression, signal transduction, antioxidant defence system, stomatal conductance, leaf senescence, grain partitioning, and water relations (Farooq *et al*., 2017; Van Oosten *et al*., 2017; Zulfiqar *et al*., 2019; Desoky *et al*., 2020; Malik *et al*., 2020; Teklić *et al*., 2020). These natural products application can be carried out with different timings: prior the exposure to stress, immediately when the stress occurs, or even after. The final composition of plant extracts is very complex and depends on the type of plant and the industrial process used for their production (Teklić *et al*., 2020).

Until now, the best-examined botanical extract which increases plants tolerance against abiotic stress is produced from moringa (Table 1). As stated by the authors, moringa-based bio-products can be beneficial for crops exposed to heat, drought, and salt stresses as well as to heavy metal contamination. Tests were conducted on several model plants, *e.g*., pepper (Desoky *et al*., 2018b), quinoa (Rashid *et al*., 2018, 2020), maize (Batool *et al*., 2016), sudangrass (Desoky *et al*., 2018b), squash (Abd El-Mageed *et al*., 2017), and sweet basil (Hassanein *et al*., 2019). As a result of extracts application, the increased tolerance to stresses, plant growth, development, yield, quality, and activity of antioxidants were observed. For example, Yasmeen *et al*. (2013) used *Moringa oleifera* to produce biostimulant. Moringa has attained vast attention being rich in cytokinins, antioxidants, macro- and micronutrients in its leaves. The authors investigated the potential effects of moringa leaf extract (30 times diluted) compared to benzyl amino purine and hydrogen peroxide. The biostimulant was used to overcome salt stress in wheat cv. Sehar-2006. Foliar application of moringa leaf extract activated the antioxidant defence system and decreased Na^+ and Cl^- accumulation in wheat shoots under moderate saline conditions (8 dS/m), allowing the achievement of the best results in terms of maize responses to salt stress. Another study (Abd El-Mageed *et al*., 2017) evaluated the leaf extract of moringa as a biostimulant for plant growth. The authors investigated moringa leaf extract to improve drought tolerance in squash plants under saline conditions. The moringa extract was applied as foliar sprayed (3%) on plant cropped both under full (100% of Etc) or deficit irrigation (80 or 60% of Etc). Treated plants exposed to deficit irrigation recorded higher growth and yield, harvest index, water use efficiency, chlorophyll fluorescence, photosynthetic pigments, soluble sugars and free proline, leaf anatomy, relative water content and membrane stability index and had lower electrolyte leakage compared to untreated plants.

The evaluation of the impact of licorice extracts on pepper, common bean, and pea under different abiotic stresses (heavy metals contamination and salt stress) is prevalent among scientists in recent years (Desoky *et al*., 2019a, 2019b; Rady *et al*., 2019). Their use generates similar effects as in the case of using moringa-based extracts. For example, Rady *et al*. (2019) evaluated the potential effects of licorice (*Glycyrrhiza glabra*) root extract (0.5%; 5 g roots/L distilled water) used for seed soaking and/or foliar spray on *Phaseolus vulgaris* plants grown on saline (EC 7.15 dS/m) soil. The authors showed significant increases in growth and yield parameters, photosynthetic pigments, free proline, total soluble carbohydrates, total soluble sugars, nutrients, and selenium, K^+/Na^+ ratio, relative water content, membrane stability index, activities of all enzymatic antioxidants, while represented significant decreases in electrolyte leakage, malondialdehyde (MDA), Na^+, hydrogen peroxide, and superoxide radical by the application of licorice root extract for seed soaking and/or foliar application compared to the controls (using distilled water) under salt stress. Another study (Desoky *et al.*, 2019a) reported the effects of licorice root extract in seed soaking using pea (*Pisum sativum*) seedlings grown under 150 mM NaCl-salinity. Licorice root extract pre-treatment enhanced seedling growth, photosynthesis, ascorbate, and glutathione and their redox states, proline, soluble sugars, compared to stressed control.

The information about the application of carrot extracts on cowpea under salt stress (Abbas and Akladious, 2013), sugar beets extracts (Noman *et al*., 2018), and *Cuscuta reflexa* herb extract (Ali *et al*., 2020) on wheat under water stress, palm pollen grains extract on sweet basil under drought stress (Taha *et al*., 2020), or alfalfa extracts on maize under salt stress (Ertani *et al*., 2013) can also be found in the scientific reports confirming the beneficial effect of PDBs on crop plants. For example, Ali *et al*. (2020) reported a study carried out to assess the effects of *Cuscuta reflexa* (a herb belonging to the family *Convolvulaceae*) extract on water-stressed wheat plants. Different levels of *C. reflexa* extract (0, 10, 20, 30, 40, and 50%), were assessed as seed priming. Low doses of *C. reflexa* extract (10, 20, and 30%) ameliorated the adverse effects of water stress on seed germination attributes and at the same time recorded better growth and yield as compared with non-treated ones. This higher performance was associated with an improvement in water relations, photosynthetic pigments, nutrient acquisition, reduced lipid peroxidation, and better antioxidative defence mechanisms. Taha *et al*. (2020) investigated the influence of palm (*Phoenix dactylifera*) pollen grains extract on basil (*Ocimum basilicum*) plants cropped under normal and water-deficit stress conditions. The extract was applied as a foliar spray at a rate of 1 g/L under full (70% of soil water-holding capacity) and deficit irrigation (50% of soil water-holding capacity) in a pot experiment. The application of the extract to deficit irrigated plants significantly increased the growth parameters and the contents of essential oil, leaf photosynthetic pigments, soluble sugars, free proline, and ascorbic acid. Antioxidant enzyme activities, relative water content, water use efficiency, and anatomical characteristics were also improved, while electrolyte leakage was significantly reduced compared to the untreated plants. Ertani *et al*. (2013) examined the effects of alfalfa (*Medicago sativa*) hydrolysate-based biostimulant containing triacontanol and indole-3-acetic acid. The extract was tested in salt-stressed (25, 75, and 150 mM of NaCl) maize (*Zea mays*) plants. Two weeks after sowing, maize was treated for 48 h with 1 mg/L of the obtained extract. The authors proved that the extract increased plant biomass due to stimulated plant nitrogen metabolism and antioxidant systems, even when plants were grown under salinity conditions.

Taking into account that crop plants are continuously exposed to different unfavourable growth conditions, the use of plant-derived biostimulants can increase plant tolerance to abiotic stresses, enhance yield and quality and bring economic and environmental benefits.

Plant extracts as plant protection products

The plant protection product (PPP), according to European Directive 91/414EEC (CEC 1994), is defined as a 'preparation containing one or more active substances which are used to protect plants or plant products against harm' (Labite *et al*., 2011).

Pesticides based on their usage can be classified as follows: herbicides, insecticides, nematicides, rodenticides, avicides, algicides, fungicides, bactericides *etc*. (Saroj *et al*., 2019; Fierascu *et al*., 2020). The application of PPPs gained immense popularity due to their economic, rapid, and effective increment of crop yields and to the decrement of losses from many pests, diseases, and weeds (Pogăcean and Gavrilescu, 2009; Oruonye and Okrikata, 2010; Pavlis *et al*., 2010; Labite *et al*., 2011; Berk *et al*., 2016; Suteu *et al*., 2020). However, their widespread usage caused an adverse effect on the environment and led to its quality deterioration, the initiation and intensification of deep soil degradation processes, air contamination, insect losses, exposure of non-target organisms to mixtures of toxic residues, insect/pathogen/weed resistance, and chronic negative effects on human and animal health (Koul *et al*., 2008; Pogăcean and Gavrilescu, 2009; Zanellato *et al*., 2009; Oruonye and Okrikata, 2010; Pavlis *et al*., 2010; Bajpai *et al*., 2011; Ibáñez and Blázquez, 2018; Hassauer and Roosen, 2020; Suteu *et al*., 2020; Zioga *et al*., 2020). Moreover, pesticides can be immobilised in soil and affect its organic matter and composition of the microbial community (Jouini *et al*., 2020). Another significant threat associated with the utilisation of this type of products is the contamination of food as well as groundwater, which safeness and quality are essential because it is widely used for domestic and agricultural purposes (Pavlis *et al*., 2010; Labite *et al*., 2011; Berk *et al*., 2016; Suciu *et al*., 2020; Suteu *et al*., 2020). The estimated annual usage of pesticides is 2.5 million tonnes while the damages caused by them reach $100 billion globally (Koul *et al*., 2008; Saroj *et al*., 2019). At present, the primary aim of plant protection is the implementation of novel and harmless methods of restricting the growth of pests in crop cultivation (Hassauer and Roosen, 2020; Kopacki *et al*., 2021). This requires the introduction of the concept of sustainable production of high-quality food in socially accountable means, rational management of natural resources, and reduction of synthetic products applications. The desired goal is to eliminate and limit the activity of destructive organisms, and to predict the time they appear and the possible extent to which they might spread (Kopacki *et al*., 2021). Sustainable development is the future for the reduction of pollution of air, plants, soil, groundwater, and animals (Oruonye and Okrikata, 2010; Berk *et al*., 2016; Andreotti, 2020; Suciu *et al*., 2020). Currently, agrotechnical, biological, breeding, chemical, mechanical, physical, and quarantine methods are used for plant protection (Kopacki *et al*., 2021; Trebbi *et al*., 2021). However, the development of substitute control strategies to decrease reliance on synthetic pesticides is the ultimate aim of recent studies (Gurjar *et al*., 2012). The use of plant extracts as biopesticides has been practised since time immemorial (Koul and Walia, 2009), but despite this, the tendency to seek novel plant-based pest control products continues to grow (Tembo *et al*., 2018). Botanicals, bioactive compounds extracted from plants, can be used as an eco-friendly alternative for synthetic plant protection products (Kim *et al*., 2003; Gurjar *et al*., 2012; du Jardin, 2015). Furthermore, plant extracts reduce crop losses, are eco-friendly and bio-degradable, often cheaper than conventional pesticides (Kim *et al*., 2003; Gurjar *et al*., 2012; Pylak *et al*., 2019; Jeyapandi and Shunmugavelu, 2020). They preserve the biological diversity of predators, reduce environmental pollution, and health risks (Jeyapandi and Shunmugavelu, 2020). They exhibit high efficacy against a wide range of pests and diseases, multiple action mechanisms, and low toxicity against non-target organisms (Suteu *et al*., 2020). It is been proven that the aromatic secondary metabolites (*e.g*., coumarins, flavones, flavonoids, flavonols, phenolic acids, phenols, tannins, and quinones), synthesised by plants, are highly active against pathogens (Gurjar *et al*., 2012; Jeyapandi and Shunmugavelu, 2020) which are responsible for the most of the plant diseases (Shuping and Eloff, 2017). Plant extracts elicit antimicrobial effects and act as defence mechanisms against pathogenic microorganisms. The application of plant extracts, especially rich in essential oils, can help in the prevention from post-harvest diseases (Kotzekidou *et al*., 2008; Koul and Walia, 2009; Gurjar *et al*., 2012). The insect-pests are responsible for significant crop damages and have a negative impact on agricultural productivity (Jeyapandi and Shunmugavelu, 2020). Currently, their control depends mostly on synthetic pesticides. It is partially caused by the not well-established alternative approaches present on the market. However, the growing interest in food produced using environmentally friendly methods as well as increasing regulatory pressure on synthetic insecticides imply a renewed potential for commercialisation of natural bio-products (Stevenson *et al*., 2017). Therefore, bioproducts suitable for application in organic agriculture may attract the attention of farmers, owners of home gardens, as well as professional farmers (Matyjaszczyk, 2018). Among pests, weeds alone are accounted for almost 34% of the crop yield decline. Recently, there is an interest in more sustainable weed management tactics with the application of plant-based products (Koul and Walia, 2009). The examples of the use of plant extracts in the overcoming of destructive pests, diseases, and weeds are summarised in Table 1.

The natural products produced from tephrosia Vogel's (*Tephrosia vogelii*) have proven insecticide activity against bean aphid (*Aphis fabae*), flea beetle (*Phyllotreta cruciferae*), melon fruit fly (*Dacus cucurbitae*), spotted cucumber beetle (*Diabrotica undecimpunctata*), bean foliage beetle (*Ootheca mutabilis*, *O. bennigseni*), and flower beetle (*Epicauta albovittata*, *E. limbatipennis*) (Alao and Adebayo, 2015; Mkenda *et al*., 2015; Tembo *et al*., 2018; Kayange *et al*., 2019). The use of bitter leaf (*Vernonia amygdalina*) and Mexican sunflower (*Tithonia diversifolia*) bio-products can be useful in the control of selected pests *e.g*., flea beetles (*Podagrica uniforma*, *P. sjostedti*), aphids (*Aphis fabae*), flower beetles (*Epicauta albovittata* and *E. limbatipennis*), foliage beetles (*Ootheca mutabilis* and *O. bennigseni*), and cowpea beetle (*Callosobruchus maculatus*) (Onunkun, 2012; Mkenda *et al*., 2015; Green *et al*., 2017; Tembo *et al*., 2018). The application of neem (*Azadirachta indica*) products was found to be efficient against aphid species (*Sitobion avenae*, *Schizaphis graminum*, *Rhopalosiphum padi*), cotton bollworm (*Helicoverpa armigera*), and fall armyworm (*Spodoptera frugiperda*) (Shah *et al*., 2017; Zuleta-Castro *et al*., 2017; Fite *et al*., 2020). Extracts obtained from pawpaw (*Carica papaya*) leaf, stem bark, root, and flower showed good potential as bio-insecticide for protecting stored maize (*Zea mays*) grains against maize weevil (*Sitophilus zeamais*) (Adenekan *et al*., 2020).

Essential oils extracted from plants, belonging to the Lamiaceae family (including *Agastache*, *Hyptis*, *Lavandula*, *Lepechinia*, *Mentha*, *Melissa*, *Ocimum*, *Origanum*, *Perilla*, *Perovskia*, *Phlomis*, *Rosmarinus*, *Salvia*, *Satureja*, *Teucrium*, *Thymus*, *Zataria* and *Zhumeria*) exhibit pesticidal activities. The compounds responsible for the pesticidal effects are aliphatic phenylpropanoids and terpenes (hydrocarbon monoterpene, monoterpenoid, hydrocarbon sesquiterpene and sesquiterpenoid) (Koul *et al*., 2008; Bajpai *et al*., 2011; Amri *et al*., 2013; Atak *et al*., 2016; Shreeya *et al*., 2016; Benvenuti *et al*., 2017; Nikolova and Berkov, 2018; Ebadollahi *et al*., 2020; Karalija *et al*., 2020). Digilio *et al*. (2008) showed that essential oils extracted from representatives of *Lamiaceae* family such as hyssop (*Hyssopus officinalis*), lavender (*Lavandula angustifolia*), marjoram (*Majorana hortensis*), lemon balm (*Melissa officinalis*), basil (*Ocimum* *basilicum*), oregano (*Origanum vulgare*), sage (*Salvia officinalis*), thyme (*Thymus vulgaris*) exhibit insecticide activity against the aphid pests *Acyrthosiphon pisum* and *Myzus persicae*.

The extracts based on garlic (*Allium sativum*) are one of the most widely used natural fungicides. Their application can help to fight late blight (*Phytophthora infestans*), early blight (*Alternaria solani*), leaf mold (*Fulvia fulva*), pepper blight (*Phytophthora capsici*), phytophthora blight (*Phytophthora infestans*), *Botrytis cinerea*, *Fusarium oxysporum*, *Verticillium dahliae*, and early blight disease (*A. solani*) (Abd-El-Khair and Haggag, 2007; Portz *et al*., 2008; Li and Zhihui, 2009; Wei *et al*., 2011; Nashwa and Abo-Elyou, 2012; Hayat *et al*., 2016, 2018). To combat the late blight (*P. infestans*) and early blight (*A. solani*), the treatment with basil (*Ocimum bacilicum*) and eucalyptus (*Eucalyptus chamadulonsis*, *E. globulus*) leaves can be considered (Abd-El-Khair and Haggag, 2007; Nashwa and Abo-Elyou, 2012).

Various weed control methods are applied to diminish the negative impact of the interference of unwanted plants on the growth and development of crops (Shreeya *et al*., 2016; El-rokiek *et al*., 2020). However, due to the low effectiveness of biological and mechanical techniques, worldwide agricultural practices are mostly based on chemical methods (Atak *et al*., 2016; Shreeya *et al*., 2016; Fierascu *et al*., 2020). The chemical interactions among plants could be used as ecological methods to limit the application of synthetic pesticides (Koul *et al*., 2008; Zanellato *et al*., 2009; Bajpai *et al*., 2011; Amri *et al*., 2013; Taban *et al*., 2013; Shreeya *et al*., 2016; Ibáñez and Blázquez, 2018; Saroj *et al*., 2019; El-rokiek *et al*., 2020; Fierascu *et al*., 2020; Mirmostafaee *et al*., 2020; Raveau *et al*., 2020; Ni *et al*., 2021). These interactions include competition (growth inhibition due to the active absorption of limited resources) and allelopathy (growth inhibition due to the release of chemicals). However, allelochemicals can also exhibit stimulatory effects on the growth of neighbouring plants (Zanellato *et al*., 2009; Amri *et al*., 2013; Atak *et al*., 2016; Shreeya *et al*., 2016; Benvenuti *et al*., 2017; Mirmostafaee *et al*., 2020). Some of the most important and common types of this compounds are: alkaloids, benzoxazinoids, glucosinolates, mamilactones, phenolic compounds, sorogoleones, and terpenes (Mirmostafaee *et al*., 2020). Plants release allelochemicals into the environment through leaf or stem leaching (caused by rain, dew, irrigation), tissue decomposition, root exudates, and volatilisation (prevalent in dry and semi-arid conditions) (Atak *et al*., 2016; Mirmostafaee *et al*., 2020). The ability of aromatic and medicinal plants to transmit allelochemicals in their essential oils (Benvenuti *et al*., 2017; Jouini *et al*., 2020; Mirmostafaee *et al*., 2020) has attracted much attention due to their phytotoxic activity against weeds and the possibility of the use as potential green pesticides (Koul *et al*., 2008; Atak *et al*., 2016; Shreeya *et al*., 2016; Benvenuti *et al*., 2017; Raveau *et al*., 2020; Ni *et al*., 2021). On average, most plants contain from 1 to 2% of essential oils (ranging from 0.01 to 10%) (Koul *et al*., 2008). EOs are synthesised by all plant organs (*e.g*., herbs, buds, flowers, fruits, leaves, twigs, bark, wood, seeds, roots) (Bajpai *et al*., 2011; Amri *et al*., 2013; Taban *et al*., 2013; Atak *et al*., 2016; Shreeya *et al*., 2016; Raveau *et al*., 2020), and mostly are extracted by hydrodistillation, water and steam distillation, as well as a solvent or supercritical fluid extraction (Miguel, 2010; Bajpai *et al*., 2011; Nikolova and Berkov, 2018; Raveau *et al*., 2020; Ni *et al*., 2021). Essential oils are stored in secretory cells, cavities, canals, epidermic cells, or glandular trichomes (Shreeya *et al*., 2016; Nikolova and Berkov, 2018; Raveau *et al*., 2020). Plants emit volatile organic compounds to attract pollinators, seed dispersers, and other beneficial organisms (Amri *et al*., 2013; Taban *et al*., 2013; Shreeya *et al*., 2016) as well as to protect themselves against heat and cold and induce defence responses (Koul *et al*., 2008). Essential oils, a source of bioactive compounds, can exert antibacterial, antifungal, herbicidal, nematicidal, and insecticidal activities which encourage their exploration and utilisation as one of the most promising natural products that could be used as an alternative to synthetic chemical pesticides (Shreeya *et al*., 2016; Ibáñez and Blázquez, 2018; Saroj *et al*., 2019; El-rokiek *et al*., 2020; Fierascu *et al*., 2020; Karalija *et al*., 2020; Raveau *et al*., 2020; Ni *et al*., 2021). The EOs global market is projected to reach 403.06 kilotonnes by 2025, thus the large-scale production could contribute to the decrement of their production costs (Fierascu *et al*., 2020). The application of EO-based herbicides could be highly beneficial because they are biodegradable, have high structural variety, exhibit minimum mammalian toxicity, and could diminish natural resistance to weeds (Shreeya *et al*., 2016; Nikolova and Berkov, 2018; Fierascu *et al*., 2020; Jouini *et al*., 2020; Karalija *et al*., 2020). Furthermore, the diverse modes of action of EOs make it more difficult for weeds to develop resistance to them (Jouini *et al*., 2020). Nevertheless, the high volatility and low water solubility of EOs can pose impediments and need to be taken into account (Fierascu *et al*., 2020). EOs are usually characterised by up to three main compounds present at relatively high concentrations in comparison to others occurring in trace amounts (Raveau *et al*., 2020). For instance, coriander (*Coriander sativum*) essential oil consists mainly of linalool (50-60%); while stone pine (*Pinus pinea*) EO contain limonene (54%), α-pinene (7%), and β-pinene (3.5%); oregano (*Origanum heracleoticum*) EO contain carvacrol (65%) and thymol (15%), peppermint (*Mentha x piperita*) EO contain menthol (59%) and menthone (19%), basil (*Ocimum basilicum*) EO contain methyl chavicol (75%), while sweet flag (*Acorus calamus*) rhizomes EO contain β-asarone (70-80%) (Koul *et al*., 2008; Raveau *et al*., 2020). Essential oils due to their inhibitory activity on seed germination and/or growth and development could be used in weed control, however, their mechanism of action remains not fully known (Amri *et al*., 2013; Jouini *et al*., 2020). The suppression of seed germination and primary root growth of certain weeds can be assigned to the presence of monoterpenes, such as α-pinene, β-pinene, 1-8-cineole, camphor, carvacrol, limonene, myrcene, and thymol suppress (Koul *et al*., 2008; Bajpai *et al*., 2011; Karalija *et al*., 2020). The phytotoxic activity of EOs is a result of the inhibition of mitochondrial respiration, followed by damages in the membrane integrity, and oxidative stress, affecting pH homoeostasis and equilibrium of inorganic ions (Amri *et al*., 2013; Fierascu *et al*., 2020; Karalija *et al*., 2020). They influence mitosis inhibition, reduction of cellular respiration and chlorophyll and RNA contents, removal of waxy cuticular layer, and polarisation of microtubules (Raveau *et al*., 2020). The phytotoxic and herbicidal effects of essential oils have been demonstrated in studies examining the effects of, for example clove, lemon-scented gum, brown mallet, lemon grass, citronella, winter savoury, thyme, rosemary, oregano, white micromeria, peppermint, basil, lemon balm, pine, boldo, cinnamon, sweet wormwood, yarrow, fennel, pistachio, terebinth, juniper, arborvitae, and common rue (Nikolova and Berkov, 2018). For instance, oregano essential oils can be used against redroot pigweed (*Amaranthus retroflexus*), white goosefoot (*Chenopodium album*), curly duck (*Rumex crispus*) (Kordali *et al*., 2008), monocots (*Triticum aestivum* and *Hordeum vulgare*) (Species *et al*., 2020), common purslane (*Portulaca oleracea*), Italian ryegrass (*Lolium multiflorum*), cockspur grass (*Echinochloa crus-galli*) (Ibáñez and Blázquez, 2017), animated oat (*Avena sterilis*), charlock mustard (*Sinapis arvensis*) (Atak *et al*., 2016), yellow star-thistle (*Centaurea salsotitialis*), wild radish

(*Raphanus raphanistrum*), Nepal Dock (*Rumex nepalensis*), and common sowthistle (*Sonchus oleraceus*) (Azirak and Karaman, 2008). The application of thyme EOs can be considered to combat, *e.g*., radish (*Raphanus sativus*), lettuce (*Lactuca sativa*), cress (*Lepidium sativum*) (De Almeida *et al*., 2010), redroot pigweed (*Amaranthus retroflexus*), common wild oat (*Avena fatua*), rye brome (*Bromus secalinus*), and cornflower (*Centaurea cyanus*) (Synowiec *et al*., 2017), thorn apple (*Datura stramonium*), and cress (*Lepidium sativum*) (Kashkooli and Saharkhiz, 2014). Amongst the various other examined oils, cinnamon oil can be here adduced due to its inhibitory activity against, *e.g*., redroot pigweed (*Amaranthus retroflexus*), wild mustard (*Sinapis arvensis*) (Campiglia *et al*., 2007), black nightshade (*Solanum nigrum*), common purslane (*Portulaca oleracea*), white goosefoot (*Chenopodium album*), common vetch (*Vicia sativa*) (Cavalieri and Caporali, 2010), and rigid ryegrass (*Lolium rigidum*) (Vasilakoglou *et al*., 2013). For the production of ecological herbicides, sorghum (*Sorghum bicolor*) can be used to control weeds of cereals (*Cyperus rotundus*) (Cheema *et al*., 2009) and wheat (*Triticum aestivum*) (Cheema and Khaliq, 2000). The products based on basil (*O. basilicum*) can reduce the growth of *Amaranthus* sp. and *Portulaca* sp. weeds (Mekky *et al*., 2019) as well as *Angallis arvensis*, *C. rotundus*, and *Cynodon dactylon* (Khare *et al*., 2019). It was shown that teak (*Tectona grandis*) extracts can lower the population of junglerice (*Echinochloa colona*) and common barnyardgrass (*Echinochloa crus-galli*) (Kole *et al*., 2016), while cardoon (*Cynara cardunculus*) products can inhibit the development of Crimson clover (*Trifolium incarnatum*) (Kaab *et al*., 2020). Based on the findings of research studies, it can be seen that essential oils exhibit herbicidal activity against different weed species and therefore could be considered for the development of natural multi-targeted herbicides.

The current review demonstrates that botanical plant protection products can be used in integrated pest management as they are cheap, easy to prepare, and environmentally friendly. It can be assumed that natural plant chemicals will play a crucial role in future pest control.

Conclusions and future directions

Modern agriculture faces two important goals - the reduction of environmental impact and the increment of the production of high-quality food for an ever-growing world population. The objective of this review was to identify if plant-derived biostimulants have the potential to sustain both of these goals. The scientific literature confirmed that the applications of PDBs may have a beneficial impact on plant growth, productivity, quality, and tolerance to various biotic and abiotic stresses. Due to their multifaceted properties, they have increasingly been considered as valuable advanced farming techniques used in worldwide agricultural production. PDBs represent a new generation of products and an eco-friendly complement to widely used agro-chemicals. In the coming few years, we can expect that plant biostimulants including both natural and synthetic substances, as well as microbial inoculants, will not only make a significant contribution to ecologically and economically sustainable crop production systems within more resilient agro-ecosystems but will also lay the cornerstone for a future large-scale sustainable agriculture catalysed by the bio-based industry.

References

Abbas SM, Akladious SA, 2013. Application of carrot root extract induced salinity tolerance in cowpea (Vigna sinensis L.) seedlings. Pakistan J. Bot. 45:795-806.

Abbas SMTM, Zaglool MA, El-Ghadban EAE, Abd El-Kareem SEH, Waly AA, 2016. Effect of foliar application with aloe leaf extract (ALE) on vegetative growth, oil percentage and anatomical leaf structure of sage (Salvia officinalis L.) plant under sand soil conditions. Hortsci. J. Suez Canal Univ. 5:9-14.

Abbas MM, Hussain WS, 2020. Biostimulants of pepper and eggplant by using plants aqueous extract. Plant Cell Biotechnol. Mol. Biol. 21:72-82.

Abd-El-Khair H, Haggag WM, 2007. Application of some Egyptian medicinal plant extracts against potato late and early blights. Res. J. Agricult. Biol. Sci. 3:166-75.

Abd El-Mageed TA, Semida WM, Rady MM, 2017. Moringa leaf extract as biostimulant improves water use efficiency, physio-biochemical attributes of squash plants under deficit irrigation. Agric. Water Manag. 193:46-54.

Abou Chehade L, Al Chami Z, De Pascali SA, Cavoski I, Fanizzi FP, 2018. Biostimulants from food processing by products: agronomic, quality and metabolic impacts on organic tomato (Solanum lycopersicum L.). J. Sci. Food Agric. 98:1426-36.

Adenekan MO, Adejumo AOD, Akande OK, 2020. Evaluation of pawpaw plant extracts against Sitophilus zeamais (Mots) Coleoptera: Curculionidae) on maize seeds. J. Multi-Discipl. Eng. Sci. Stud. 6:3186-92.

Alao FO, Adebayo TA, 2015. Comparative efficacy of Tephrosia vogelii and Moringa oleifera against insect pests of watermelon (Citrullus lanatus Thumb). Int. Lett. Nat. Sci. 35:71-8.

Ali M, Cheng ZH, Hayat S, Ahmad H, Ghani MI, Liu T, 2019. Foliar spraying of aqueous garlic bulb extract stimulates growth and antioxidant enzyme activity in eggplant (Solanum melongena L.). J. Integr. Agr. 18:1001-13.

Ali Q, Perveen R, El-Esawi MA, Ali S, Hussain SM, Amber M, Iqbal N, Rizwan M, Alyemeni MN. El-Serehy HA, Al-Minsed F, Ahmad P, 2020. Low doses of Cuscuta reflexa extract act as natural biostimulants to improve the germination vigor, growth, and grain yield of wheat grown under water stress: photosynthetic pigments, antioxidative defence mechanisms, and nutrient acquisition. Biomolecules 10:1212.

Alzahrani Y, Rady MM, 2019. Compared to antioxidants and polyamines, the role of maize grain-derived organic biostimulants in improving cadmium tolerance in wheat plants. Ecotoxicol. Environ. Saf. 182:1-13.

Amin MA, 2018. Comparative studies on growth, metabolism and yield of sesame plant by using seaweed, plant extracts and some growth regulators. Al-Azhar Bull. Sci. 29:19-28.

Amri I, Hamrouni L, Hanana M, Jamoussi B, 2013. Reviews on phytotoxic effects of essential oils and their individual components: news approach for weeds management. Int. J. Appl. Biol. Pharm. Technol. 4:96-114.

Andreotti C, 2020. Management of abiotic stress in horticultural crops: Spotlight on biostimulants. Agronomy 10:1-3.

Apone F, Tito A, Carola A, Arciello S, Tortora A, Filippini L, Monoli I, Cucchiara M, Gibertoni S, Chrispeels MJ, Colucci G, 2010. A mixture of peptides and sugars derived from plant cell walls increases plant defence responses to stress and attenuates ageing-associated molecular changes in cultured skin cells. J. Biotechnol. 145:367-76.

Atak M, Mavi K, Uremis I, 2016. Bio-herbicidal effects of oregano and rosemary essential oils on germination and seedling growth of bread wheat cultivars and weeds. Rom. Biotechnol. Lett. 21:11149-59.

Azad M, Sarker S, 2017. Efficacy of some botanical extracts on plant growth, yield and pest management in eggplant field. J. Environ. Sci. Nat. Resour. 10:137-40.

Azirak S, Karaman S, 2008. Allelopathic effect of some essential oils and components on germination of weed species. Acta Agric. Scand. Sect. B Soil Plant Sci. 58:88-92.

Babilie R, Jbour M, Trabi BA, 2015. Effect of foliar spraying with licorice root and seaweed extractson growth and seed production of onion (Allium cepa L.). Int. J. ChemTech Res. 8:557-63.

Bajpai VK, Baek KH, Kim ES, Han JE, Kwak M, Oh K, Kim JC, Kim S, Choi GJ, 2012. In vivo antifungal activities of the methanol extracts of invasive plant species against plant pathogenic fungi. Plant Pathol. J. 28:317-21.

Bajpai VK, Kang S, Xu H, Lee SG, Baek KH, Kang SC, 2011. Potential roles of essential oils on controlling plant pathogenic bacteria Xanthomonas species: a review. Plant Pathol. J. 27:207-24.

Barrajón-Catalán E, Herranz-López M, Joven J, Segura-Carretero A, Alonso-Villaverde C, Menéndez JA, Micol V, 2014. Molecular promiscuity of plant polyphenols in the management of age-related diseases: far beyond their antioxidant properties. Adv. Exp. Med. Biol. 824:141-59.

Basra SMA, Lovatt C, 2016. Exogenous applications of Moringa oleifera leaf extract and cytokinins improve plant growth, yield and fruit quality of cherry tomato (Solanum lycopersicum). HortTechnol. 26:327-37.

Batool A, Wahid A, Farooq M, 2016. Evaluation of aqueous extracts of moringa leaf and flower applied through medium supplementation for reducing heat stress induced oxidative damage in maize. Intl. J. Agric. Biol. 18:757-64.

Beni C, Casorri L, Masciarelli E, Ficociello B, Masetti O, Neri U, Aromolo R, Rinaldi S, Papetti P, Cichelli A, 2020, Characterization of thyme and tansy extracts used as basic substances in zucchini crop protection. J. Agricult. Stud. 8:95-110.

Ben-Jabeur M, Vicente R, Lopez-Cristoffanini C, Alesami N, Djebali N, Gracia-Romero A, Serret MD, Lopez-Carbonell M, Araus JL, Hamada, W, 2019. A novel aspect of essential oils: coating seeds with thyme essential oil induces drought resistance in wheat. Plants-Basel 8:371.

Benvenuti S, Cioni PL, Flamini G, Pardossi A, 2017. Weeds for weed control: asteraceae essential oils as natural herbicides. Weed Res. 57:342-53.

Berk P, Hocevar M, Stajnko D, Belsak A, 2016. Development of alternative plant protection product application techniques in orchards, based on measurement sensing systems: a review. Comput. Electron. Agric. 124:273-88.

Bhatnagar-Mathur P, Vadez V, Sharma KK, 2008. Transgenic approaches for abiotic stress tolerance in plants: Retrospect and prospects. Plant Cell Rep. 27:411-24.

Brown P, Saa S, 2015. Biostimulants in agriculture. Front. Plant Sci. 6:1-3.

Bulgari R, Cocetta G, Trivellini A, Vernieri P, Ferrante A, 2015. Biostimulants and crop responses: A review. Biol. Agric. Hortic. 31:1-17.

Bulgari R, Morgutti S, Cocetta G, Negrini N, Farris S, Calcante A, Spinardi A, Ferrari E, Mignani I, Oberti R, Ferrante A, 2017. Evaluation of borage extracts as potential biostimulant using a phenomic, agronomic, physiological, and biochemical approach. Front. Plant Sci. 8:935.

Bulgari R, Franzoni G, Ferrante A, 2019. Biostimulants application in horticultural crops under abiotic stress conditions. Agronomy 9:1-30.

Campiglia E, Mancinelli R, Cavalieri A, Caporali F, 2007. Use of essential oils of cinnamon, lavender and peppermint for weed control. Ital. J. Agron. 2:171.

Cavalieri A, Caporali F, 2010. Effects of essential oils of cinnamon, lavender and peppermint on germination of Mediterranean weeds. Allelopath. J. 25:441-52.

Cárdenas CD, Tumbaco M, Pozo-Rivera WE, Morejón M, Rojas M, Gooty JM, Cuaycal A, 2018. Antifungal activity and biostimulating effect generated by two botanical extracts in Alpinia purpurata and Heliconia wagneriana cultivation. Org. Agric. 8:325-33.

Cheema ZA, Khaliq A, 2000. Use of sorghum allelopathic properties to control weeds in irrigated wheat in a semi arid region of Punjab. Agricult. Ecosys. Environ. 79:105-12.

Cheema ZA, Mushtaq MN. Farooq M, Hussain A, Din IU, 2009. Purple nutsedge management with allelopathic sorghum. Allelop. J. 23:305-12.

Chrysargyris A, Charalambous S, Xylia P, Litskas V, Stavrinides M, Tzortzakis N, 2020. Assessing the biostimulant effects of a novel plant-based formulation on tomato crop. Sustainability 12:8432.

Colla G, Hoagland L, Ruzzi M, Cardarelli M, Bonini P, Canaguier R, Rouphael Y, 2017. Biostimulant action of protein hydrolysates: Unraveling their effects on plant physiology and microbiome. Front. Plant Sci. 8:1-14.

Cramer GR, Urano K, Delrot S, Pezzotti M, Shinozaki K, 2011. Effects of abiotic stress on plants: a systems biology perspective. BMC Plant Biol. 11:1-14.

Cruz-Estrada A, Gamboa-Angulo M, Borges-Argáez R, Ruiz-Sánchez E, 2013. Insecticidal effects of plant extracts on immature whitefly Bemisia tabaci Genn. (Hemiptera: Aleyroideae). El. J. Biotechnol. 16(1).

Deba F, Xuan TD, Yasuda M, Tawata S, 2008. Chemical composition and antioxidant, antibacterial and antifungal activities of the essential oils from Bidens pilosa Linn. var. radiata. Food Control 19:346-52.

De Almeida LFR, Frei F, Mancini E, De Martino L, De Feo V, 2010. Phytotoxic activities of Mediterranean essential oils. Molecules 15:4309-23.

De Pascale S, Rouphael Y, Colla G, 2017. Plant biostimulants: Innovative tool for enhancing plant nutrition in organic farming. Eur. J. Hortic. Sci. 82:277-85.

Desoky ESM, Elrys AS, Mohamed GF, Rady MM, 2018a. Exogenous application of moringa seed extract positively alters fruit yield and its contaminant contents of Capsicum annuum plants grown on a saline soil contaminated with heavy metals. Adv. Plants Agricult. Res. 8:591-601.

Desoky ESM, Merwad ARM, Rady MM, 2018b. Natural biostimulants improve saline soil characteristics and salt stressed-sorghum performance. Commun. Soil Sci. Plant Anal. 49:967-83.

Desoky ESM, Elrys AS, Rady MM, 2019a. Licorice root extract boosts Capsicum annuum L. production and reduces fruit contamination on a heavy metals-contaminated saline soil. Int. Lett. Nat. Sci. 73:1-16.

Desoky ESM, ElSayed AI, Merwad ARMA, Rady MM, 2019b. Stimulating antioxidant defenses, antioxidant gene expression, and salt tolerance in Pisum sativum seedling by pretreatment using licorice root extract (LRE) as an organic biostimulant. Plant Physiol. Biochem. 142:292-302.

Desoky ESM, EL-Maghraby LMM, Awad AE, Abdo AI, Rady MM, Semida WM, 2020. Fennel and ammi seed extracts modulate antioxidant defence system and alleviate salinity stress in cowpea (Vigna unguiculata). Sci. Hortic. 272:1-11.

Digilio MC, Mancini E, Voto E, De Feo V, 2008. Insecticide activity of Mediterranean essential oils. J. Plant Interacti. 3:17-23.

Di Mola I, Ottaiano L, Cozzolino E, Senatore M, Giordano M, El-nakhel C, Sacco A, Rouphael Y, Colla G, 2019. Plant-Based biostimulants influence the agronomical, physiological, and qualitative responses of baby rocket leaves under diverse nitrogen conditions. Plants 8:1-15.

Dipak Kumar H, Aloke P, 2020. Role of biostimulant formulations in crop production: An overview. Int. J. Agric. Sci. Vet. Med. 8:38-46.

Di Vittori L, Mazzoni L, Battino, M, Mezzetti B, 2018. Pre-harvest factors influencing the quality of berries. Sci. Hortic. 233:310-22.

Donno D, Beccaro GL, Mellano MG, Canterino S, Cerutti AK, Bounous G, 2013. Improving the nutritional value of kiwifruit with the application of agroindustry waste extracts. J. Appl. Bot. Food Qual. 86:11-5.

Drobek M, Frąc M, Cybulska J, 2019. Plant biostimulants: Importance of the quality and yield of horticultural crops and the improvement of plant tolerance to abiotic stress-a review. Agronomy 9:1-18.

du Jardin P, 2015. Plant biostimulants: definition, concept, main categories and regulation. Sci. Hortic. 196:3-14.

Ebadollahi A, Ziaee M, Palla F, 2020. Essential oils extracted from different species of the Lamiaceae plant family as prospective bioagents against several detrimental pests. Molecules 25:1556.

El-Azim A, Khater WM, And Badawy RMR, 2017. Effect of bio-fertilization and different licorice extracts on growth and productivity of Foeniculum vulgare, Mill. Plant. Middle East J. Agric. Res. 6:1-12.

EL Boukhari ME, Barakate M, Bouhia Y, Lyamlouli K, 2020. Trends in seaweed extract based biostimulants: manufacturing process and beneficial effect on soil-plant systems. Plants-Basel 9:359.

El-rokiek KG, Ibrahim ME, El-din SAS, El-sawi SA, 2020. Using anise (Pimpinella anisum L.) essential oils as natural herbicide. J. Mater. Environ. Sci. 11:1689-98.

Elzaawely AA, Ahmed ME, Maswada HF, Al-Araby AA, Xuan TD, 2018. Growth traits, physiological parameters and hormonal status of snap bean (Phaseolus vulgaris L.) sprayed with garlic cloves extract. Arch. Agron. Soil Sci. 64:1068-82.

Ertani A, Schiavon M, Muscolo A, Nardi S, 2013. Alfalfa plant-derived biostimulant stimulate short-term growth of salt stressed Zea mays L. plants. Plant Soil. 364:145-58.

Ertani A, Sambo P, Nicoletto C, Santagata S, Schiavon M, Nardi S, 2015. The use of organic biostimulants in hot pepper plants to help low input sustainable agriculture. Chem. Biol. Technol. Agric. 2:1-10.

Ertani A, Pizzeghello D, Francioso O, Tinti A, Nardi S, 2016. Biological activity of vegetal extracts containing phenols on plant metabolism. Molecules 21:1-14.

Ertani A, Schiavon M, Nardi S, 2017. Transcriptome-wide identification of differentially expressed genes in Solanum lycopersicon L. in response to an alfalfa-protein hydrolysate using microarrays. Front. Plant Sci. 8:1159.

EU, 2019. Regulation of the European parliament and of the council laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2019:170:TOC

Farooq M, Rizwan M, Nawaz A, Rehman A, Ahmad R, 2017. Application of natural plant extracts improves the tolerance against combined terminal heat and drought stresses in bread wheat. J. Agro. Crop Sci. 203:528-38.

Fierascu RC, Fierascu IC, Dinu-Pirvu CE, Fierascu I, Paunescu A, 2020. The application of essential oils as a next-generation of pesticides: Recent developments and future perspectives. Zeitschrift Fur Naturforsch. Sect. C J. Biosci. 75:183-204.

Findura P, Hara P, Szparaga A, Kocira S, Czerwińska E, Bartoš P, Nowak J, Treder K, 2020a. Evaluation of the effects of allelopathic aqueous plant extracts, as potential preparations for seed dressing, on the modulation of cauliflower seed germination. Agric. 10:1-9.

Findura P, Kocira S, Hara P, Pawłowska A, Szparaga A, Kangalov P, 2020b. Extracts from Artemisia vulgaris L. in potato cultivation - preliminary research on biostimulating effect. Agricult. 10:356.

Fite T, Tefera T, Negeri M, Damte T, 2020. Effect of Azadirachta indica and Milletia ferruginea extracts against Helicoverpa armigera (Hubner) (Lepidoptera: Noctuidae) infestation management in chickpea. Cogent Food Agricult. 6:1712145.

Ganagi TI, Jagadeesh KS, 2018. Effect of spraying Lantana fermented extract on growth and yield of green gram (Vigna radiata L.) in pots. Int. J. Curr. Microbiol. Appl. Sci. 7:1187-93.

Godlewska K, Biesiada A, Michalak I, Pacyga P, 2019. The effect of plant-derived biostimulants on white head cabbage seedlings grown under controlled conditions. Sustainability 11:5317.

Godlewska K, Biesiada A, Michalak I, Pacyga P, 2020a. The effect of botanical extracts obtained through ultrasound-assisted extraction on white head cabbage (Brassica oleracea L. Var. capitata L.) seedlings grown under controlled conditions. Sustainability 12:1871.

Godlewska K, Pacyga P, Michalak I, Biesiada A, Szumny A, Pachura N, Piszcz U, 2020b. Field-scale evaluation of botanical extracts effect on the yield, chemical composition and antioxidant activity of celeriac (Apium graveolens L. Var. rapaceum). Molecules 25:4212.

Green PWC, Belmain SR, Ndakidemi PA, Farrell IW, Stevenson PC, 2017. Insecticidal activity of Tithonia diversifolia and Vernonia amygdalina. Ind. Crops Prod. 110:15-21.

Gurjar MS, Ali S, Akhtar M, Singh KS, 2012. Efficacy of plant extracts in plant disease management. Agric. Sci. 03:425-33.

Hassanein RA, Abdelkader AF, Faramawy HM, 2019. Moringa leaf extracts as biostimulants-inducing salinity tolerance in the sweet basil plant. Egypt. J. Bot. 59:303-18.

Hassauer C, Roosen J, 2020. Toward a conceptual framework for food safety criteria: Analyzing evidence practices using the case of plant protection products. Saf. Sci. 127:1-17.

Hayat S, Ahmad H, Ali M, Hayat K, Khan MA, Cheng Z, 2018. Aqueous garlic extract as a plant biostimulant enhances physiology, improves crop quality and metabolite abundance, and primes the defence responses of receiver plants. Appl. 8:1505.

Hayat S, Cheng Z, Ahmad H, Ali M, Chen X, Wang M, 2016. Garlic, from remedy to stimulant: Evaluation of antifungal potential reveals diversity in phytoalexin allicin content among garlic cultivars; allicin containing aqueous garlic extracts trigger antioxidants in cucumber. Front. Plant Sci. 7:1235.

Hussain M, Farooq M, Basra SMA, Lee DJ, 2013. Application of moringa allelopathy in crop production. In: Z. A. Cheema, M. Farooq & A. Wahid (Eds.), Allelopathy: current trends and future applications. Springer-Verlag, Heidelberg, Germany, pp. 469-484.

Ibáñez MD, Blázquez MA, 2017. Herbicidal value of essential oils from oregano-like flavour species. Food Agric. Immunol. 28:1168-80.

Ibáñez MD, Blázquez MA, 2018. Phytotoxicity of essential oils on selected weeds: Potential hazard on food crops. Plants 7:1-15.

Isman MB, 1995. Leads and prospects for the development of new botanical insecticides. Rev. Pestic. Toxicol. 3:1-20.

Jafarbeigi F, Samih MA, Zarabi M, Esmaeily S, 2012. The effect of some herbal extracts and pesticides on the biological parameters of Bemisia tabaci (Genn.) (Hem.: Aleyrodidae) pertaining to tomato grown under controlled conditions. J. Plant Prot. Res. 52:375-80.

Jang SJ, Kuk YI, 2019. Growth promotion effects of plant extracts on various leafy vegetable crops. Hort. Sci. Technol. 6:322-36.

Jabran K, Farooq M, 2013. Implications of potential allelopathic crops in agricultural systems. In: Z. A. Cheema, M. Farooq & A. Wahid (Eds.), Allelopathy: Current trends and future applications. Springer-Verlag, Heidelberg, Germany, pp. 349-388.

Jadeja GC, Maheshwari RC, Naik SN, 2011. Extraction of natural insecticide azadirachtin from neem (Azadirahta indica A. Juss) seed kernels using pressurized hot solvent. J. Supercrit. Fluids 56:253-8.

Jeyapandi R, Shunmugavelu M, 2020. Effect of the plant extract Pongamia pinnata against polyphagous pest Mylabris Indica. Rev. Biotechnol. Biochem. 1:2019-21.

Jouini A, Verdeguer M, Pinton S, Araniti F, Palazzolo E, Badalucco L, Laudicina VA, 2020. Potential effects of essential oils extracted from Mediterranean aromatic plants on target weeds and soil microorganisms. Plants 9:1-24.

Kaab SB, Rebey IB, Hanafi M, Hammi KM, Smaoui A, Fauconnier ML, De Clerck C, Jijakli MH, Ksouri R, 2020. Screening of Tunisian plant extracts for herbicidal activity and formulation of a bioherbicide based on Cynara cardunculus. South Afr. J. Bot. 128:67-76.

Karalija E, Dahija S, Parić A, Ćavar Zeljković S, 2020. Phytotoxic potential of selected essential oils against Ailanthus altissima (Mill.) Swingle, an invasive tree. Sustain. Chem. Pharm. 15:1-8.

Kashkooli AB, Saharkhiz MJ, 2014. Essential oil compositions and natural herbicide activity of four Denaei Thyme (Thymus daenensis Celak.) Ecotypes. J. Essent. Oil-Bearing Plants 17:859-74.

Kayange CDM, Njera D, Nyirenda SP, Mwamlima L, 2019. Effectiveness of Tephrosia vogelii and Tephrosia candida extracts against common bean aphid (Aphis fabae) in Malawi. Adv. Agricult. 6704834.

Khan S, Basra SMA, Afzal I, Wahid A, 2017. Screening of moringa landraces for leaf extract as biostimulant in wheat. Int. J. Agric. Biol. 19:999-1006.

Khare P, Srivastava S, Nigam N, Singh AK, Singh S, 2019. Impact of essential oils of E. citriodora, O. basilicum and M. arvensis on three different weeds and soil microbial activities. Environ. Technol. Innov. 14:100343.

Kim S-I, Roh J-Y, Lee H-S, Ahn Y-J, Kim S-I, Kim D-H, 2003. Insecticidal activities of aromatic plant extracts and essential oils against Sitophilus oryzae and Callosobruchus chinensis. J. Stored Prod. Res. 39:293-303.

Kole RK, Paul P, Saha S, Das S, Mukhopadhyay SK, 2016. Chemistry and bio-efficacy of teak leaf for weed control in wheat. Allelop. J. 39:191-203.

Kopacki M, Pawłat J, Skwaryło-Bednarz B, Jamiołkowska A, Stępniak PM, Kiczorowski P, Golan K, 2021. Physical crop postharvest storage and protection methods. Agronomy 11:1-16.

Kordali S, Cakir A, Ozer H, Cakmakci R, Kesdek M, Mete E, 2008. Antifungal, phytotoxic and insecticidal properties of essential oil isolated from Turkish Origanum acutidens and its three components, carvacrol, thymol and p-cymene. Bioresour. Technol. 99:8788-95.

Kotzekidou P, Giannakidis P, Boulamatsis A, 2008. Antimicrobial activity of some plant extracts and essential oils against food-borne pathogens in vitro and on the fate of inoculated pathogens in chocolate. LWT - Food Sci. Technol. 41:119-27.

Koul O, Walia S, 2009. Comparing impacts of plant extracts and pure allelochemicals and implications for pest control. CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 4:3-30.

Koul P, Walia S, Dhaliwal GS, 2008. Essential oils as green pesticides: potential and constraints. Biopestic. Int. 4:63-84.

Labite H, Butler F, Cummins E, 2011. A review and evaluation of plant protection product ranking tools used in agriculture. Hum. Ecol. Risk Assess. 17:300-27.

Li S, Zhihui C, 2009. Allium sativum extract as a biopesticide affecting pepper blight. Int. J. Veget. Sci. 15:13-23.

Lucini L, Rouphael Y, Cardarelli M, Bonini P, Baffi C, Colla G, 2018. A vegetal biopolymer-based biostimulant promoted root growth in melon while triggering brassinosteroids and stress-related compounds. Front. Plant Sci. 9:472.

Malik A, Mor VS, Tokas J, Punia H, Malik S, Malik K, Sangwan S, Tomar S, Singh P, Singh N, Himangini, Vikram, Nidhi, Singh G, Vikram, Kumar V, Sandhya, Karwasra A, 2020. Biostimulant-treated seedlings under sustainable agriculture: A global perspective facing climate change. Agronomy 11:1-24.

Matyjaszczyk E, 2018. Plant protection means used in organic farming throughout the European Union. Pest Manag. Sci. 74:505-10.

Mazrou RM, 2019. Moringa leaf extract application as a natural biostimulant improves the volatile oil content, radical scavenging activity and total phenolics of coriander. J. Med. Plants Stud. 7:45-51.

Mekky MS, Hassanien AMA, Kamel EM, Ismail AEA, 2019. Allelopathic effect of Ocimum basilicum L. extracts on weeds and some crops and its possible use as new crude bio-herbicide. Annals Agricult. Sci. 64:211-21.

Merwad ARMA, 2018. Using Moringa oleifera extract as biostimulant enhancing the growth, yield and nutrients accumulation of pea plants. J. Plant Nutr. 41:425-31.

Michalak I, Chojnacka K, 2014. Algal extracts: Technology and advances. Eng. Life Sci. 14:581-91.

Miguel MG, 2010. Antioxidant and anti-inflammatory activities of essential oils: a short review. Molecules 15:9252-87.

Mirmostafaee S, Azizi M, Fujii Y, 2020. Study of allelopathic interaction of essential oils from medicinal and aromatic plants on seed germination and seedling growth of lettuce. Agronomy 10:1-23.

Mittler R, 2006. Abiotic stress, the field environment and stress combination. Trends Plant Sci. 11:15-9.

Mkenda P, Mwanauta R, Stevenson PC, Ndakidemi P, Mtei K, Belmain SR, 2015. Extracts from field margin weeds provide economically viable and environmentally benign pest control compared to synthetic pesticides. PLoS One 10:e0143530.

Mohamed MH, Badr EA, Sadak MSh, Khedr HH, 2020. Effect of garlic extract, ascorbic acid and nicotinamide on growth, some biochemical aspects, yield and its components of three faba bean (Vicia faba L.) cultivars under sandy soil conditions. Bull. Nat. Res. Cent. 44:100.

Mona MA, 2013. The potential of Moringa oleifera extract as a biostimulant in enhancing the growth, biochemical and hormonal contents in rocket (Eruca vesicaria subsp. sativa) plants. Int. J. Plant Physiol. Biochem. 5:42-9.

Nashwa SMA, Abo-Elyou KAM, 2012. Evaluation of various plant extracts against the early blight disease of tomato plants under greenhouse and field conditions. Plant Prot. Sci. 48:74-9.

Ni ZJ, Wang X, Shen Y, Thakur K, Han J, Zhang JG, Hu F, Wei ZJ, 2021. Recent updates on the chemistry, bioactivities, mode of action, and industrial applications of plant essential oils. Trends Food Sci. Technol. 110:78-89.

Nikolova M, Berkov S, 2018. Use of essential oils as natural herbicides. Ecol. Balk. 10:259-65.

Noman A, Ali Q, Naseem J, Javed MT, Kanwal H, Islam W, Aqeel M, Khalid N, Zafar S, Tayyeb M, Iqbal N, Buriro M, Maqsood J, Shahid S, 2018. Sugar beet extract acts as a natural bio-stimulant for physio-biochemical attributes in water stressed wheat (Triticum aestivum L.). Acta Physiol. Plant. 40:1-17.

Onunkun O, 2012. Evaluation of aqueous extracts of five plants in the control of flea beetles on okra (Abelmoschus esculentus (L.) Moench). J. Biopest. 5:62-7.

Oparaeke AM, 2007. Synergistic activity of aqueous extracts mixtures of some Nigerian plants against Maruca vitrata and Clavigralla tomentosicollis on field cowpea, Vigna unguiculata (L.) Walp. Arch. Phytopathol. Plant Protect. 40:257-63.

Oruonye ED, Okrikata E, 2010. Sustainable use of plant protection products in Nigeria and challenges. J. Plant Breed. Crop Sci. 2:267-72.

Parađiković N, Teklić T, Zeljković S, Lisjak M, Špoljarević M, 2018. Biostimulants research in some horticultural plant species - A review. Food Energy Secur. 8:1-17.

Pardo-García AI, Martínez-Gil AM, Cadahía E, Pardo F, Alonso GL, Salinas MR, 2014. Oak extract application to grapevines as a plant biostimulant to increase wine polyphenols. Food Res. Int. 55:150-60.

Parrado J, Bautista J, Romero EJ, García-Martínez AM, Friaza V, Tejada M, 2008. Production of a carob enzymatic extract: potential use as a biofertilizer. Bioresour. Technol. 99:2312-8.

Pavela R, 2016. History, presence and perspective of using plant extracts as commercial botanical insecticides and farm products for protection against insects - a review. Plant Protect. Sci. 52:229-41.

Pavlis M, Cummins E, McDonnell K, 2010. Groundwater vulnerability assessment of plant protection products: a review. Hum. Ecol. Risk Assess. 16:621-50.

Pogăcean MO, Gavrilescu M, 2009. Plant protection products and their sustainable and environmentally friendly use. Environ. Eng. Manag. J. 8:607-27.

Portz D, Koch E, Slusarenko AJ, 2008. Effects of garlic (Allium sativum) juice containing allicin on Phytophthora infestans and downy mildew of cucumber caused by Pseudoperonospora cubensis. Eur. J. Plant Pathol. 122:197-206.

Povero G, Mejia JF, Di Tommaso D, Piaggesi A, Warrior P, 2016. A systematic approach to discover and characterize natural plant biostimulants. Front. Plant Sci. 7:1-9.

Pretorius JC, 2007. Seed suspensions from 'Lupinus albus', isolated compounds thereof and use as biological plant strengthening agent. Patent No. WO2007090438 A1, 59. Available from: http://www.freepatentsonline.com/ WO2007090438A1.html

Pretorius JC, 2013. Extracts and compounds from 'Agapanthus africanus' and their use as biological plant protecting agents. Patent No. WO2007003286 A2. Available from: http://www.freepatentsonline.com/WO2007003286A2.html

Pylak M, Oszust K, Frąc M, 2019. Review report on the role of bioproducts, biopreparations, biostimulants and microbial inoculants in organic production of fruit. Rev. Environ. Sci. Biotechnol. 18:597-616.

Rady MM, Desoky ES, Elrys AS, Boghdady MS, 2019. Can licorice root extract be used as an effective natural biostimulant for salt-stressed common bean plants?. S. Afr. J. Bot. 121:294-305.

Rashid N, Basra SMA, Shahbaz M, Iqbal S, Hafeez MB, 2018. Foliar applied moringa leaf extract induces terminal heat tolerance in Quinoa. Int. J. Agric. Biol. 20:157-64.

Rashid N, Wahid A, Basra SMA, Arfan M, 2020. Foliar spray of moringa leaf extract, sorgaab, hydrogen peroxide and ascorbic acid improve leaf physiological and seed quality traits of quinoa (Chenopodium quinoa) under terminal heat stress. Int. J. Agricult. Biol. 23:811-9.

Raveau R, Fontaine J, Lounès-Hadj Sahraoui A, 2020. Essential oils as potential alternative biocontrol products against plant pathogens and weeds: a review. Foods 9:1-31.

Rehman HU, Alharby HF, Alzahrani Y, Rady MM, 2018. Magnesium and organic biostimulant integrative application induces physiological and biochemical changes in sunflower plants and its harvested progeny on sandy soil. Plant Physiol. Biochem. 126:97-105.

Rouphael Y, Colla G, 2018. Synergistic biostimulatory action: Designing the next generation of plant biostimulants for sustainable agriculture. Front. Plant Sci. 871:1-7.

Rouphael Y, Colla G, 2020. Toward a sustainable agriculture through plant biostimulants: From experimental data to practical applications. Agronomy 10:1-10.

Roy S, Mukhopadhyay A, Gurusubramanian G, 2010. Field efficacy of a biopesticide prepared from Clerodendrum viscosum Vent. (Verbenaceae) against two major tea pests in the sub Himalayan tea plantation of North Bengal, India. J. Pest Sci. 83:371-7.

Saijo Y, Loo EP, 2020. Plant immunity in signal integration between biotic and abiotic stress responses. New Phytol. 225:87-104.

Saroj A, Oriyomi OV, Nayak AK, Haider SZ, 2019. Phytochemicals of plant-derived essential oils: a novel green approach against pests. In: Chukwuebuka Egbuna and Barbara Sawicka. Natural remedies for pest, disease and weed control. Elsevier Inc., Amsterdam, The Netherlands, pp. 65-79.

Sánchez-Gómez R, Zalacain A, Pardo F, Alonso GL, Salinas MR, 2017. Moscatel vine-shoot extracts as a grapevine biostimulant to enhance wine quality. Food Res. Int. 98:40-9.

Sequi P, Rea E, Trinchera A, Rivera CM, Salerno A, 2009. Exploring biostimulant effect of a brassicacea plant extract: use of maize seedling development as reference bioassay. pp 737-744 in XI International Symposium on Plant Bioregulators in Fruit Production 884.

Shah FM, Razaq M, Ali A, Han P, Chen JL, 2017. Comparative role of neem seed extract, moringa leaf extract and imidacloprid in the management of wheat aphids in relation to yield losses in Pakistan. PLoS One 12:e0184639.

Sharma A, Kumar V, Shahzad B, Ramakrishnan M, Singh Sidhu GP, Bali AS, Handa N, Kapoor D, Yadav P, Khanna K, Bakshi P, Rehman A, Kohli SK, Khan EA, Parihar RD, Yuan H, Thukral AK, Bhardwaj R, Zheng B, 2020. Photosynthetic response of plants under different abiotic stresses: a review. J. Plant Growth Regul. 39:509-31.

Shreeya A, Batish DR, Singh HP, 2016. Research paper alleopathic effect of aromatic plants: role of volatile essential oils. J. Glob. Biosci. 5:4386-95.

Shuping DSS, Eloff JN, 2017. The use of plants to protect plants and food against fungal pathogens: a review. Afr. J. Tradit. Complement. Altern. Med. 14:120-7.

Souri MK, Bakhtiarizade M, 2019. Biostimulation effects of rosemary essential oil on growth and nutrient uptake of tomato seedlings. Sci. Hort. 243:472-6.

Stevenson PC, Isman MB, Belmain SR, 2017. Pesticidal plants in Africa: A global vision of new biological control products from local uses. Ind. Crops Prod. 110:2-9.

Suciu N, Farolfi C, Zambito Marsala R, Russo E, De Crema M, Peroncini E, Tomei F, Antolini G, Marcaccio M, Marletto V, Colla R, Gallo A, Capri E, 2020. Evaluation of groundwater contamination sources by plant protection products in hilly vineyards of Northern Italy. Sci. Total Environ. 749:1-11.

Suteu D, Rusu L, Zaharia C, Badeanu M, Daraban GM, 2020. Challenge of utilization vegetal extracts as natural plant protection products. Appl. Sci. 10:1-21.

Suzuki N, Rivero RM, Shulaev V, Blumwald E, Mittler R, 2014. Abiotic and biotic stress combinations. New Phytol. 203:32-43.

Synowiec A, Kalemba D, Drozdek E, Bocianowski J, 2017. Phytotoxic potential of essential oils from temperate climate plants against the germination of selected weeds and crops. J. Pest Sci. 90:407-19.

Taban A, Saharkhiz MJ, Hadian J, 2013. Allelopathic potential of essential oils from four Satureja spp. Biol. Agric. Hortic. 29:244-57.

Taha RS, Alharby HF, Bamagoos AA, Medani RA, Rady MM, 2020. Elevating tolerance of drought stress in Ocimum basilicum using pollen grains extract; a natural biostimulant by regulation of plant performance and antioxidant defence system. S. Afr. J. Bot. 128:42-53.

Teklić T, Parađiković N, Špoljarević M, Zeljković S, Lončarić Z, Lisjak M, 2020. Linking abiotic stress, plant metabolites, biostimulants and functional food. Ann. Appl. Biol. 1-23.

Tembo Y, Mkindi AG, Mkenda PA, Mpumi N, Mwanauta R, Stevenson PC, Ndakidemi PA, Belmain SR, 2018. Pesticidal plant extracts improve yield and reduce insect pests on legume crops without harming beneficial arthropods. Front. Plant Sci. 9:1425.

Thanaa S, Kassim N, AbouRayya M, Abdalla A, 2017. Influence of foliar application with moringa (Moringa oleifera L.) leaf extract on yield and fruit quality of Hollywood plum cultivar. J. Hortic. 4:1-7.

Thanaa SM, Nabila EK, Abou Rayya MS, Eisa RA, 2016. Response of nonpareil seedlings almond to foliar application of licorice root extract and bread yeast suspend under South Sinai conditions. J. Innov. Pharm. Biol. Sci. 3:123-32.

Trebbi G, Negri L, Bosi S, Dinelli G, Cozzo R, Marotti I, 2021. Evaluation of Equisetum arvense (Horsetail macerate) as a copper substitute for pathogen management in field-grown organic tomato and durum wheat cultivations. Agric. 11:1-14.

Ugolini L, Cinti S, Righetti L, Stefan A, Matteo R, D'Avino L, Lazzeri L, 2015. Production of an enzymatic protein hydrolyzate from defatted sunflower seed meal for potential application as a plant biostimulant. Ind. Crop. Prod. 75:15-23.

Van Oosten MJ, Pepe O, De Pascale S, Silletti S, Maggio A, 2017. The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. Chem. Biol. Technol. Agric. 4:1-12.

Vasilakoglou I, Dhima K, Paschalidis K, Ritzoulis C, 2013. Herbicidal potential on Lolium rigidum of nineteen major essential oil components and their synergy. J. Essent. Oil Res. 25:1-10.

Vinocur B, Altman A, 2005. Recent advances in engineering plant tolerance to abiotic stress: Achievements and limitations. Curr. Opin. Biotechnol. 16:123-32.

Wei TT, Cheng ZH, Khan MA, Ma Q, Ling H, 2011. The inhibitive effects of garlic bulb crude extract on Fulvia fulva of tomato. Pak. J. Bot. 43:2575-80.

Yakhin OI, Lubyanov AA, Yakhin IA, Brown PH, 2017. Biostimulants in plant science: a global perspective. Front. Plant Sci. 7:1-32.

Yasmeen A, Basra SMA, Farooq M, Rehman HU, Hussain N, 2013. Exogenous application of moringa leaf extract modulates the antioxidant enzyme system to improve wheat performance under saline conditions. Plant Growth Regul. 69: 225-33.

Zanellato M, Masciarelli E, Casorri L, Boccia P, Sturchio E, Pezzella M, Cavalieri A, Fabio C, 2009. The essential oils in agriculture as an alternative strategy to herbicides: a case study. Int. J. Environ. Heal. 3:198-213.

Zhu JK, 2016. Abiotic stress signaling and responses in plants. Cell 167:313-24.

Zioga E, Kelly R, White B, Stout JC, 2020. Plant protection product residues in plant pollen and nectar: A review of current knowledge. Environ. Res. 189:1-16.

Zuleta-Castro C, Rios D, Hoyos R, Rozco-Sanchez F, 2017. First formulation of a botanical active substance extracted from neem cell culture for controlling the armyworm. Agron. Sustain. Dev. 37:40.

Zulfiqar F, Casadesús A, Brockman H, Munné-Bosch S, 2019. An overview of plant-based natural biostimulants for sustainable horticulture with a particular focus on moringa leaf extracts. Plant Sci. 295:1-48.