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.

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; Paradiković 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; Paradiković et al., 2018; Roupaha and Colla, 2018; Di Mola et al., 2019; Zulfigar 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; Paradiković et al., 2018; Zulfigar 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; Paradiković 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 Chojnicka, 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 Khalig, 2009; 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., Oparaene, 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 (Oparaene, 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         |
|---------------|-------------------|-----------------------|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
| 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, distilled water (1:20, w/v), 30 min, centrifugation; mechanical homogenization, 1 min, 28 000 rpm, centrifugation | Field, foliar application, 0.5% | Celereic (Aegopodium podagraria) | Increased yield of leaves rosettes and roots, the weight of leaves rosettes and roots, the content of chlorophyll a and 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 macromolecules, the composition of volatile compounds and fatty acids | Godlewski 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 | Mohanned 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 | Elizawey 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 |
| Morins 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, 3.5% (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 |
| Morins 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% (w/v) Tween-20-20, 50, 100, 200, 300 g/L | Coriandrum (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 |
| Morins 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, antioxyin content, antioxidant activity content; reduced titratable acidity with reduced fruit drop | Thanaa et al., 2017 |
| Plant Specie(s)                        | Description                                                                 | Plant Species                                                                 | Description                                                                                                                                                                                                 | Reference |
|---------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| Moringa leaf (*Moringa oleifera*)     | Rinsed with water leaves kept in a freezer, overnight, mechanical extraction | 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/25 mL, stirring with a homogenizer, filtration) | 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                              | 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 ascorbic 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    | 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, 90°C, the mixture was left for 24 h to settle, filtration | Onion (*Allium cepa*)                                                         | Increased plant height, length of the tallest leaf, number of leaves, flowering, seed production, germination percentage                                                                                                                                                 | Babille et al., 2015 |
| Licorice root (*Glycyrrhiza glabra*)   | Roots blended in distilled water (5 g or 10 g/L), 90°C, 24 h, filtration    | 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 | Thanas et al., 2016 |
| Licorice root (*Glycyrrhiza glabra*)   | Dried powdered roots extracted with distilled water (cold and hot) (10 g/L), filtration | Field, foliar application, 5, 10 and 15 g/L, filtration                      | Improved growth, essential oil and chemical composition                                                                                                                                                      | El-Azim et al., 2017 |
| Red grape skin (*Vitis vinifera*)      | Hawthorn - fully controlled enzymatic hydrolysis, the red grape skin material and blueberry fruits - cool extraction | Fennel (*Foeniculum vulgare*)                                                | Increased root and leaf biomass, chlorophyll, phenol acids and sugars content; induced phenylalanine ammonia lyase (PAL) activity                                                                                   | Ertani et al., 2016 |
| Blueberry fruits (*Vaccinium vitis-idaea*) | Hawthorn leaves (*Craeagus monogyna*) - cool extraction                        | 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 | Potato                                                                       | Increased the chlorophyll a and chlorophyll b content and its total concentration, the carotenoids content, induced plants the changes in the concentration of polyphenols | Findura et al., 2020b |
| Olive leaves (*Olea europaea*), 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                                                     | 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 printing/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 (*Pisum sativum*) | Increased plant height, number of leaves, dry matter, chlorophyll content, number and weight of pods per plant, number of seeds per pod, grain yield | Garagi and Jagadeesh, 2018 |
| **Borage leaves and flowers** (*Borago officinalis*) | Leaves minced, macerated in distilled 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 polyphenolase, 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 hirsuta*), hina leaves (*Lawsonia inermis*), Chinese chestnut leaves (*Fritillaria nepalensis*), wild celery seeds (*Curum 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 (Protein France S.A.S.) obtained by maceration of biomass in water at high temperature Not available | Vineyard, foliar spray, 25 and 100% | 8-year-old grapevines (*Vitis vinifera*) | Aflatoxin composition, lowered alcohol content and acidity, increased colour intensity and stability, lowered free, increased content of polyphenols | Pardo-Garcia et al., 2014 |
| **Apple seeds, celza seeds, rice husks** | Not available | Orchard, foliar spray | Kiwifruit (*Actinidia deliciosa*) | Increased the fruit weight, ascobic 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, GAs, zeatin; increased seed yield and oil content - oleic and linolenic fatty acids; decreased other saturated, mono unsaturated, polyunsaturated fatty acids; improved 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 melongena*) | Increased the percentage of germination, root length, root dry weight, leaf area | Abbus and Hussein, 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 - 300 mL 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 | Scari et al. and Bakhtiar zade, 2019 |
| **Rosemary** (*Rosmarinus officinalis*), eucalyptus (*Eucalyptus globulus*) | Commercial product - 'Agriculture Greentech P', 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 | Clayser et al., 2020 |
| 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 | Parooq et al., 2017 |
| Lycorice 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, Ca, Pb and Ni concentrations in leaves and fruits | Desoky et al., 2019a |
| Lycorice 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, chlorophyll 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, peroxidase radical | Radly et al., 2019 |
| Lycorice 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 (chlorophyll, carotenoids, FV/FR), ascorbate and glutathione and their redox states, proline, soluble sugars, a-TOC, and enzyme activities; upregulated transcript levels of CAT, SOD, APX, GR, DHA-R, and ProPQ 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, Ca, Pb and Ni contents in plant leaves and fruits | Desoky et al., 2018a |
| Moringa fresh leaf (Moringa oleifera), sorgum 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 (1:1.5, 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 H2O2 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 drum, filtration of extracted solution gel | Field trials, foliar spray, 10, 20 and 40 mL/L, and soil conditions | Saga (*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) | Gridding fresh moringa leaves with water (10 kg/1 L), filtration, centrifugation | Pot experiments, seed printing, 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 minimized the membrane peroxidation | Baitool 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 | Sadan grass (*Sorghum vulgare var. sudanense*) | Increased growth characteristics, photochemical activity, content of RNA, DNA, phytosterol, 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 |
| Plant extracts under biostress condition |
|------------------------------------------|
| **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 minced leaves in cold water (10, 40 and 100 g/2 L), room temp., filtration | Field, spray, 0.5, 2, 2% (w/v, insect pest - bean aphid (*Aphis fabae*)), Common bean (*Phaseolus vulgaris*) | Reduced aphid population per plant, 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 (muscot cloth) | Field, spray, 5, 10, 20% (w/v), insect pests - flea beetle (*Phyllotreta crucifera*), melon fruit fly (*Drosophila undecimpunctata*), Watermelon (*Citrullus lanatus*) | Protected against the insects | Also and Adeniyi, 2015 |
| **Sweet orange** (*Citrus sinensis*), tree-gamhar (*Gonelmia arborea*), chilli pepper (*Capsicum annuum*), Afromic 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 (muscat cloth) | Field, spray, lima bean pod borer (*Maruca vitrana*), African pod bug (*Clavigralla tomentosa*) | Cowpea (*Vigna unguiculata*) | Effectively reduced the incidences of *M. vitrana* and *C. tomentosa* on flowers and pods, increased grain yield | Oparaene, 2007 |
| Plant Name | Description | Application and Result |
|------------|-------------|------------------------|
| *Goit weed (Ageratum conyzoides)* | Leaf | Field, spray, flea beetles (*Podagrica uniforma*, *P. sjoestedti*) | Okra (*Abelmoschus esculentus*) |
| *Arabidopsis thaliana* | Leaf | Inhibition of root growth | Arabidopsis thaliana |
| *Fusarium oxysporum* | Leaf | Reduced mycelial growth and inhibited spore germination of both fungal species | Radiant (*Solanum tuberosum*) |
| *Garlic (Allium sativum)* | Leaf | Effectively controlled the leaf mold in tomato caused by *F. fulva* | Tomato (*Solanum lycopersicum*) |
| *Garlic (Allium sativum)* | Leaf | Reduced mycelial growth and inhibited spore germination of both fungal species | Radiant (*Solanum tuberosum*) |
| *Non-commercial use only* | | | |
| *Non-commercial use only* | | | |
| Herbicide | Extraction method | Extracts | Plants | Application | Effect | Notes |
|-----------|-------------------|----------|--------|-------------|--------|-------|
| 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 | Porte et al., 2008 |
| Garlic (Allium sativum) | Fresh garlic ground in a mortar and pestle, homogenized in distilled water (10 g/100 mL), centrifugation, filtration | Glasshouse pot trial, spray, 50, 150, 300 mg/mL fungi: B. am:'.$ | 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 pestle, homogenized with distilled water (10 g/100 mL), centrifugation, filtration | Pot experiments (a glasshouse), foliar spray, fertigation, 100 μg/mL, Phytophthora capsici | 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 Phytophthora capsici inoculation | Hayat et al., 2018 |
| Amazon cinnamon leaves (Ocotea quixos), pepper (Piper carinatum) | Extraction via maceration and herbal distillation | Field, spray, 40, 60%, Ficus var., Cappadocia spp. | Red ginger (Alpinia purpurata), heliconia (Heliconia wagneriana) | Showed an inhibitory activity against Ficus var. and Cappadocia spp., 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, Sclerotinia trifoliorum | 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 F. graminearum, S. trifoliorum and T. turgidum | 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 (B. cinerea), tomato late blight (Phytophthora infestans), wheat leaf rust (Puccinia triticina), barley powdery mildew (Blumeria graminis f. sp. hordei), pepper anthracnose (Colletotrichum coccodes) | Rice (Oryza sativa), tomato (Lycopersicon esculentum), barley (Hordeum sativum), wheat (Triticum aestivum), pepper (Capsicum annuum) | Reduced the 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 Phytophthora capsici inoculation | Bajpai et al., 2012 |
| Sweat basil (Ocimum basilicum), noem (Zea violacea indica), eucalyptus (Eucalyptus chaunulus), jimsonweed (Datura stramonium), cedlar (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 lycopersicum) | Significantly reduced the early blight disease, increased the yield of tomato | Nashwa and Abo-Elloy, 2012 |
| Herbicide | Chaffed sorghum, soaking in water (1:20, w/v), 24 h, filtration | Pot culture, spray, 25 mL/pot | Weed of cereals - purple mastegue (Cyperus rotundus) | Reduced the purple mastegue 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 past weeds (Panicum virgatum, Phalaris minor, Rumex dentatus, Chenopodium album) | Controlling weeds of wheat (Triticum aestivum) | Controlled weeds, increased wheat yield | Cheema and Khaliq, 2009 |
| Teak (Tectona grandis) | Powdered leaf leaves, extraction in Scotch apparatus, methanol, (2 kg/2 L), three batches, 6 h, solvent evaporation | Field trial, spray, weeds (Echinochloa crus-galli, Echinochloa crus-galli) | Wheat | Reduced weed population | Ko et al., 2016 |
| Basel (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 weight of Amaranthus sp. and Portulaca sp. weeds | Meldy et al., 2019 |
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, 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.

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, 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

nolics, ascorbic acid, tocopherols, selenium, glutathione, free
proline, soluble sugars; phytohormones such as auxins, gib-
berellins, 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, gib-
berellins, and abscisic acid and their metabolites was also con-
firmed by Basra and Lovatt (2016) in young fully expanded
moringa leaves.
family as *T. diversifolia* and *V. amygdalina* contains bioactive constituents such as β-caryophyllene and γ-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-cubebe, 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 methanic 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 seeds, 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. Meikkylä 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-dimethyltetrauran-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-trimethyl 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*), and *Mentha piperita* demonstrated the phytotoxicity on weeds. The major constituent in essential oils extracted from *E. citriodora* was citronellall, 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; Yahkin et al., 2017; Rouphael and Colla, 2018; Zulfiqar et al., 2019; Dipak Kumar and Alope, 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 (Yahkin 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 Alope, 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 Alope, 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 *Alfaifa* 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 biostimulating 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 *Nictiana tabacum* cv. BY-2 cell wall gly-
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 (Thanan 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), knottgrass (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 (Godlewksa et al., 2019; Godlewksa 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 activity 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. Borago 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 “viti-cultural bio stimulants” 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, acetylated anthocyanins, flavonols, 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 (Apium graveolens) 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 (Godlewksa 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, hypersomotic, 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; Zulfiquar 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 spray (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 stress-es, 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, acicides, algicides, fungicides, bactericides etc. (Saroj et al., 2019; Fiersacu 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 (Pogacean and Gavrielsec, 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; Pogacean and Gavrilucea, 2009; Zanellunga 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; Zoga 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; Suci 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; Suci 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 Shumugavelu, 2020). They preserve the biological diversity of predators, reduce environmental pollution, and health risks (Jeyapandi and Shumugavelu, 2020). They exhibit high efficiency against a wide range of pests and diseases, multiple action mechanisms, and low toxicity against non-target organisms (Suteu et al., 2020). It has 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 Shumugavelu, 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 Shumugavelu, 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. benignesi), and flower beetle (Epicauta albivittata, E. limbatispina) (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. sjostedtii), aphids (Aphis fabae), flower beetles (Epicauta albivittata and E. limbatispina), foliage beetles (Ootheca mutabilis and O. benignesi), 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-pesticide for protecting stored maize (Zea mays) grains against maize weevil (Sitophilus zeamais) (Adenean 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 Zumeria) exhibit pesticidal activities. The compounds responsible for the pesticidal effects are aliphatic phenylpropanoids and terpenes (hydrocarbon monoterpene, monoterpenoid, hydrocarbon sesquiterpene and sesqui-terpenoid) (Koul et al., 2008; Bajpai et al., 2011; Amri et al., 2013; Atak et al., 2016; Shreya 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...

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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 Zhihu, 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 basilicum) and eucalyptus (Eucalyptus chamadoulonsis, 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-rokeriek 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; Ibahiez and Blazquez, 2018; Saroj et al., 2019; El-rokeriek et al., 2020; Fierascu et al., 2020; Karalija 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 (Coriandrum sativum) essential oil consists mainly of farnoal (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 methyl 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 monoterpens, 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 homeostasis 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) (Ibahiez and Blazquez, 2017), animated oat (Avena sterilis), charlock mustard (Sinapis arvensis) (Atak et al., 2016), yellow star-thistle (Centaurea salsolitopsis), wild radish 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, nematocidal, 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; Ibahiez and Blazquez, 2018; Saroj et al., 2019; El-rokeriek 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 (Coriandrum sativum) essential oil consists mainly of farnoal (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 methyl 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). 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more resilient agro-ecosystems but will also lay the cornerstone for both natural and synthetic substances, as well as microbial inoculants. In the advanced farming techniques used in worldwide agricultural properties, they have increasingly been considered as valuable. The scientific 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 catalyst by the bio-based industry.

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 catalyst by the bio-based industry.

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