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Review article

Prospects for the use of plant-derived extracts as inducers of productivity and sustainability of agricultural crops

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Abstract. Nowadays, modern agriculture, faced with declining economic output and deteriorating environmental conditions, requires sustainable productivity growth. One promising direction is to find alternatives to traditional agrochemicals. Plant extracts are a promising solution offering multifunctional benefits due to the diversity of secondary metabolites. This review discusses the chemistry of extracts and production methods, including traditional maceration/percolation and more rapid methods for heat-sensitive compounds. Particular attention is paid to the phytostimulatory and biostimulatory effects of extracts, such as stimulation of cell division, modulation of stress-related genes, improvement of mineral nutrition by stimulating rhizosphere microbiota, increasing photosynthetic efficiency, and activation of salicylic and jasmonic acid pathways. Antimicrobial and allelopathic properties are also discussed. Key challenges such as biochemical instability, dosing issues, and lack of standardized protocols are highlighted. Solutions are proposed, including the development of formulated products, the use of omics analysis, and the creation of databases. Ultimately, it is emphasized that extracts are versatile tools for sustainable farming systems that require further standardization and integration with digital technologies to unlock their full potential.

Keywords: Plant extracts, biostimulants, phytopstimulants, allelopathic effects, sustainable agriculture, secondary metabolites

Introduction

Modern agriculture faces significant challenges, such as the need to increase the productivity of agricultural crops while meeting rising demands for environmental safety, addressing climate change, and reducing the chemical load on agroecosystems [1–3]. Traditional methods of plant protection and growth stimulation based on synthetic pesticides and fertilizers often lead to

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negative consequences, such as pollution of soils and water bodies, development of resistance in pathogens and pests, and reduction of biodiversity [4–7]. This situation dictates an urgent need to develop and implement innovative, sustainable solutions that could ensure high yields without harming the environment and human health.

In this context, plant extracts represent an extremely promising, but still underutilized alternative [4,6]. Plant extracts contain a rich spectrum of secondary metabolites, natural biologically active compounds with polyfunctional effects, from growth stimulation and increased plant resistance to stress to direct antimicrobial and insecticidal effects [8–10]. However, despite their obvious advantages, the widespread practical use of plant extracts in agricultural systems is constrained by a number of key problems. These include biochemical instability of active components, difficulties with precise dosing due to nonlinear effects, and a lack of scientifically sound protocols for their use in the field [11,12].

This article aims to systematize modern knowledge about the chemical composition and methods of obtaining plant extracts, to summarize their functional, antimicrobial, and allelopathic effects on plants. Particular attention will be paid to the physiological and biochemical changes occurring in plants under the influence of extracts, as well as to the current problems of standardization and variability of their action. The article will propose specific ways to solve these problems, including the development of new formulations and the introduction of modern analytical approaches, which will reveal the full potential of plant extracts as a key element of sustainable agroecological strategies.

Chemical composition of extracts and methods of their production

The composition of plant extracts varies depending on the botanical species, the part of the plant used (leaves, roots, fruits, flowers), growing conditions, time of collection, and extraction technology. [13–16]. The most common groups of compounds are polyphenols, alkaloids, saponins, terpenoids, and essential oils [10,17]. These secondary metabolites have different effects depending on their chemical nature (Figure 1).

Polyphenols and their representatives, such as flavonoids, tannins, and phenolic acids, have antioxidant and antimicrobial activity against gram-positive bacteria [18]. While alkaloids are neurotoxic to pests and can modulate the hormonal balance of plants, which shows their double-positive effect [19–21]. Saponins, as another type of secondary metabolite, affect the permeability of cell membranes, play a role in protecting against pathogens [22]. Terpenoids and essential oils regulate growth, have phytohormonal activity, and can suppress the development of phytopathogens, which is similar to the effect of saponins [23]. The extraction technology must be of primary importance for obtaining certain effects.

In general, with the development of science and technology, extraction methods have also developed. Extraction methods vary depending on the nature of the compounds and their physical and chemical properties; that is, there is no universal method for obtaining all compounds, which is logical [24–26]. We can divide them into classical methods and accelerated extraction methods, with the allocation of a separate group for the extraction of volatile compounds.

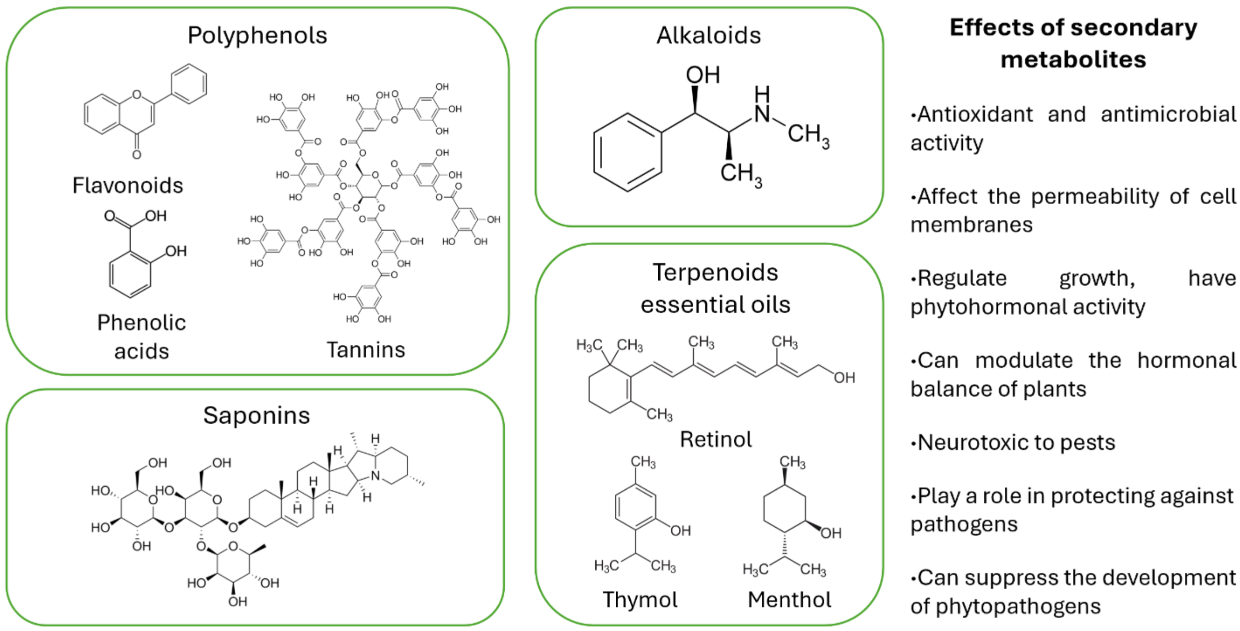

Figure 1. Secondary metabolites and their effects [13-23]

Classic extraction methods include maceration and percolation, which can be performed using a variety of solvents [26–28]. Maceration is the process of steeping plant material in a solvent for a period of time to extract the active substances [29]. Percolation, on the other hand, involves passing a solvent through a layer of plant material, ensuring a continuous renewal of the extracting agent [30]. Solvents often used include aqueous solutions, alcohol solutions of varying concentrations, and acetone solutions, the choice of which depends on the polarity and solubility of the target components [31].

The second group of extraction methods, used for heat-sensitive components, often employs accelerated extraction methods such as microwave-assisted extraction (MAE), ultrasonic extraction (UAE), and supercritical fluid extraction (SFE), which minimize thermal exposure [32–34]. MAE uses microwave radiation to rapidly and uniformly heat the solvent and matrix, which reduces extraction time and reduces the degradation of heat-sensitive compounds [35]. UAE is based on the cavitation effect created by ultrasound waves, which promotes the destruction of cell walls and improves mass transfer, which also allows extraction to be carried out at lower temperatures [36,37]. SFE uses supercritical fluids, most often carbon dioxide, as a solvent; this method is especially valuable for heat-sensitive substances, since extraction occurs at moderate temperatures and upon completion of the process, the solvent is easily separated without residue, preventing thermal degradation [38–40].

Hydrodistillation is a classic method for extracting volatile compounds such as essential oils from plant material. In this process, plant material is placed directly into water, which is then heated to the boiling point [41,42]. The resulting steam, passing through the plant material, carries with it volatile aromatic components, which are then condensed and collected as a mixture of water and essential oil, easily separated due to the different densities of the components [42–44].

Importantly, all secondary metabolite extraction stages are processes that undergo standardization of extracts and are a key step to ensure their consistent quality and efficacy. In particular, standardization can be achieved by spectrophotometric and chromatographic determination of the content of specific biomarkers [45]. Spectrophotometry allows for the quantitative assessment of the concentration of substances that absorb light in a certain wavelength range, based on the dependence of the absorption intensity on concentration [46,47]. Chromatographic methods, such as high-performance liquid chromatography-mass spectrometry (HPLC-MS) and gas chromatography-mass spectrometry (GC-MS), provide accurate separation of extract components, allowing for the identification and quantification of individual biomarkers, including chlorogenic acid, quercetin, and eugenol, which is critical for confirming the authenticity and standardization of herbal preparations [45,47,48]. The resulting extracts can then be used as biostimulants and phytostimulants.

Biostimulating and phytostimulating effects of extracts

Biostimulants and phytostimulants based on plant extracts have a complex systemic effect on plant growth and development (Figure 2), starting with the activation of cell division and elongation, which leads to enhanced growth and the formation of a more powerful root system and aboveground mass [49–51]. One of the key mechanisms of their action is the modulation of the expression of stress-induced genes, increasing plant resistance to adverse environmental factors such as drought or salt stress [52–54]. In addition, biostimulants and phytostimulants significantly improve the mineral nutrition of plants, promoting more efficient absorption and assimilation of nutrients, which in turn leads to increased photosynthetic efficiency and increased biomass [55–57]. It is important to note that the extracts activate the metabolic pathways of salicylic and jasmonic acids, key signaling molecules that regulate immune responses and plant adaptation to abiotic and biotic stresses [58–60].

Enhanced growth and formation of a more powerful root system and aboveground mass by biostimulants/phytostimulants from plant extracts occurs due to activation of division and expansion of plant cells [60]. This process occurs due to increased synthesis of two key phytohormones: gibberellins and cytokinins [50,61]. Gibberellins stimulate cell expansion, promoting stem elongation, leaf growth, and fruit development by weakening cell walls [6,62,63]. Cytokinins actively participate in cell division, stimulating their proliferation and formation of new shoots, which leads to increased branching and total plant biomass [6,50,60]. Thus, the combined action of these hormones provides a comprehensive approach to growth stimulation, covering both an increase in the number of cells and their subsequent expansion, which ultimately contributes to the overall development of the plant.

Modulation of stress-induced gene expression by biostimulants and phytostimulants may occur through activation of genes such as Dehydration-responsive element-binding (DREB), NAC, and WRKY, which play a central role in stress adaptation [52,64,65]. For example, genes of the DREB family are activated in response to drought and low temperatures, triggering cascades of reactions that help cells cope with dehydration and drought stress [66–68]. NAC and WRKY genes are large families of transcription factors involved in the regulation of various stress responses, including protection against osmotic and oxidative stress [69–71]. Enhanced expression of these genes allows plants to more efficiently synthesize protective proteins and antioxidants, minimizing damage and maintaining metabolic activity under stressful conditions.

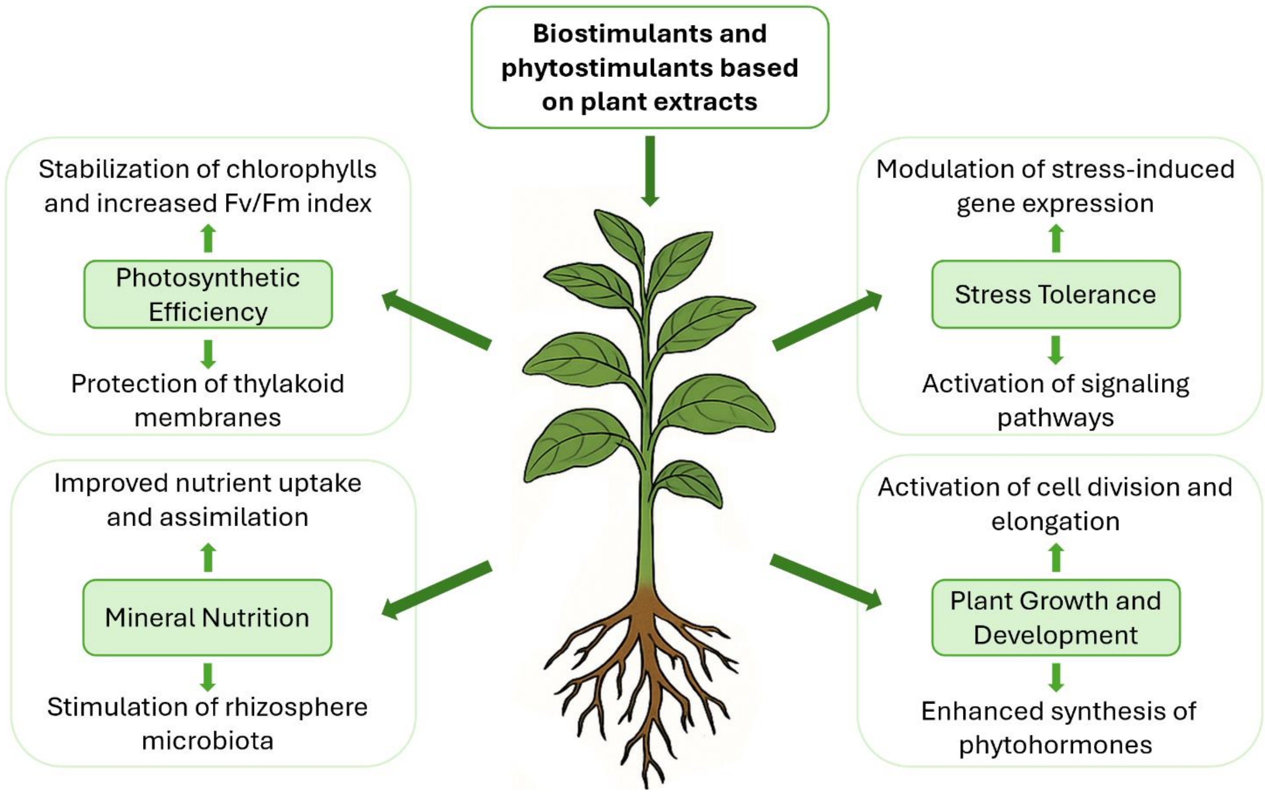

Figure 2. Biostimulating and phytostimulating effects of plant-derived extracts on agricultural plants

The use of plant extracts significantly improves the mineral nutrition of plants, which is most likely due to the stimulation of the rhizosphere microbiota [72–75]. This is especially noticeable when using extracts with a high content of organic acids and polysaccharides [76]. These compounds serve as a source of nutrition for the soil microbiome, activating the vital activity of microorganisms in the rhizosphere, promoting the dissolution of hard-to-reach nutrients and their more efficient absorption by plants [76–78].

The effects of using plant extracts on increasing the efficiency of plant photosynthesis have also been noted due to several key mechanisms [79,80]. Firstly, stabilizing the state of chlorophylls, the main pigments responsible for light absorption, prevents their premature destruction and thus maintains a high capacity for photosynthetic activity [79]. Secondly, the extracts lead to an increase in the Fv/Fm index, which is a measure of the maximum quantum efficiency of photosystem II, indicating an improvement in the use of light energy [80]. Finally, the plant extracts may preserve the thylakoids' membrane structure under the action of phenolic antioxidants contained in the extracts, protect the photosynthetic apparatus from oxidative damage, and ensure its optimal functioning even under stressful conditions [81–85].

Antimicrobial and fungicidal action

Plant extracts show significant effectiveness in combating various pathogens and can serve as a sustainable replacement for traditional plant protection products [86–88]. The effects of the extracts are varied and aimed at different ways of suppressing pathogenic organisms. Essential oils derived from plants such as thyme, oregano, and basil play a special role [89–93]. They are known for their strong fungicidal activity, capable of inhibiting the growth of fungi that cause common and destructive diseases such as root and leaf rot [89–93]. This makes them a valuable tool for the prevention and control of fungal infections.

Another striking example is neem leaf extract *(Azadirachta indica*) [94–97]. Its components not only inhibit pathogens but also disrupt the fungal division cycle, preventing their reproduction. In addition, they cause the degradation of sporangia - the structures responsible for the formation and release of spores, thereby effectively limiting the spread of infection [94–97]. This indicates a profound effect on the life cycle of the pathogen.

Antibacterial activity is also an important property of plant extracts. Extracts from plants such as garlic, ginger, and chili peppers exhibit a strong bactericidal effect, which is due to the presence of specific bioactive compounds [98–100]. In garlic, these are allicin compounds, in chili peppers - capsaicin, and in all of the above plants - various phenolic acids [101–105]. These substances can destroy the cell walls of bacteria and inhibit their metabolism, preventing the development of bacterial diseases [18,106–108].

The conducted phytopathological studies convincingly prove the effectiveness of these approaches. Regular use of plant extracts can reduce plant disease incidence by ~40-90%, with the specific indicator depending on the type of crop and the specific pathogen [109–111]. It is important to note that the effectiveness is enhanced by integrating extracts with biopreparations from *Bacillus* and *Trichoderma* [112–116]. Such complex use creates a synergistic effect, providing more reliable and comprehensive protection of plants from diseases.

Allelopathic effects and growth regulation

Plant extracts have unique allelopathic effects that allow them to influence the growth and development of crops, horticultural plants, and weeds (Figure 3) [117,118]. These effects are due to the presence of allelochemicals, biologically active compounds secreted by plants [117]. Allelochemicals can act as natural herbicides, suppressing the growth of weeds [118]. This opens up prospects for the development of environmentally friendly weed control strategies, reducing dependence on synthetic pesticides. Suppression mechanisms may include inhibition of weed seed germination, slowing down their growth, or disrupting their physiological processes [119].

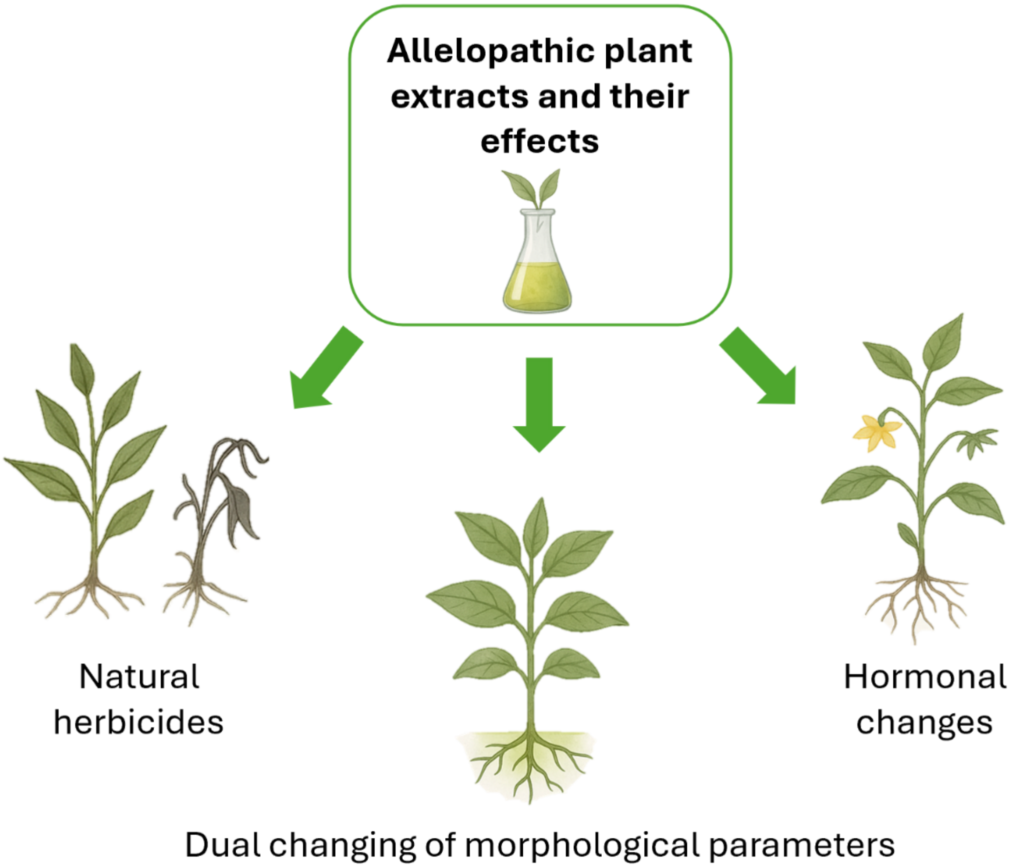

Figure 3. Allelopathic and growth-regulatory effects of plant extracts

In addition to the above-described effects on weeds, allelochemicals can cause morphological changes in the root systems of plants. These changes can be either positive (e.g., stimulation of lateral root growth for better nutrient uptake) or negative, depending on the concentration of the extract and the sensitivity of the crop [118,120,121]. Thus, these compounds can finely modulate the architecture of the root system, which is critical for plant adaptation to environmental conditions.

Moreover, allelochemicals can inhibit or stimulate the synthesis of endogenous hormones in plants. A striking example of such effects is black walnut *(Juglans nigra)* extracts, which contain a compound called juglone [122]. Juglone is known for its ability to inhibit root cell mitosis, which leads to slower root growth and generally suppressed plant development, especially in sensitive species [122]. Another example is aqueous extracts of wormwood, which, as studies show, can cause a decrease in endogenous auxins in tomato [123]. Auxins are key hormones regulating shoot and root growth, so a decrease in their levels can affect plant development [123,124].

It is worth noting that allelopathic properties should be carefully considered when selecting concentrations and methods of application of extracts to the agrosystem. Incorrect application may lead to undesirable effects on crop plants. A precise understanding of dosage and interaction with specific crops will allow the allelopathic properties of extracts to be used to optimize plant growth and effectively manage weeds in sustainable agriculture.

Extracts as elements of sustainable agriculture

Plant extracts are a key element of agroecological strategies, offering sustainable and effective solutions for modern agriculture [88,125,126]. They are compatible with organic farming and are certified in the European Union, confirming their safety and compliance with strict environmental standards [127]. Extracts can be combined with microbiological preparations, creating a synergistic effect for more comprehensive protection and stimulation of plant growth [117,118]. Their effectiveness against a wide range of pathogens without the development of resistance is a critical quality, as they act on multiple targets, reducing the likelihood of the emergence of resistant strains [86–88].

Field trials have convincingly demonstrated the practical value of plant extracts, which leads to a ~17-40% increase in crop yields [128–130]. As mentioned, the use of extracts also reduces the need for fungicides, reducing the chemical load on the agroecosystem and reducing production costs [109–111]. Additionally, an increase in soil bioactivity is observed, indicated by the growth of beneficial fungi and bacteria populations, which helps improve soil structure and nutrient cycling [72–76,78]. Prospective areas in this area include extracting from non-food residues, such as oilseed cakes or weeds [131–133]. Using these resources not only reduces waste but is also fully consistent with the principles of the circular economy, turning what was previously considered waste into valuable bioactive products for agriculture.

Problems of standardization and variability of action

The use of plant extracts in agriculture, despite their significant potential, faces several key problems that need to be addressed for their widespread and effective application. One of the main issues is the biochemical instability of extracts [134,135]. Many bioactive compounds contained in plant materials, such as polyphenols, flavonoids, terpenes, or alkaloids, are sensitive to light, heat, oxygen, and humidity [134–137]. This leads to their degradation during storage, significantly reducing the effectiveness and shortening the shelf life of the products. For example, allicin from garlic, known for its antimicrobial properties, quickly oxidizes in air and loses activity [100,101,138]. Similarly, some terpenoids from essential oils, such as linalool or geraniol, easily volatilize or decompose under the influence of light, reducing the biopesticide potential of the extract [139–141]. This instability makes it difficult to produce products with predictable quality and expiration dates.

The second problem is the difficulty of dosing. The action of plant extracts is often dose-dependent and non-linear [80,142]. This means that a small change in concentration can lead to a completely different effect: from optimal stimulation to no effect at all or even inhibition of growth. For example, low concentrations of seaweed extract can stimulate seed germination and root growth, while higher concentrations can inhibit this growth [143–145]. Without precise data on the required dosages specific to each crop and environmental conditions, it is extremely difficult for farmers to apply these products effectively and safely, risking either wasting the product or even damaging the crop.

Finally, there is a lack of clinically validated application protocols in agrosystems. Unlike synthetic pesticides and fertilizers, which have clear and proven application guidelines, most plant extracts do not have standardized recommendations based on large-scale, long-term field trials [146,147]. This makes it difficult to standardize and predict their performance across different climates, soil types, and crops, making their use empirical rather than scientifically based.

To overcome these challenges, a number of strategic solutions are proposed. First, this is the development of controlled-release formulations. These can be microencapsulated forms, nanoemulsions, liposomes, or hydrogels that stabilize the active components, protecting them from degradation [148]. For example, encapsulation of essential oils in polymer or cyclodextrin shells can significantly prolong their activity, reduce volatility, and ensure gradual release in the soil or on the leaf surface [149,150]. Such formulations allow for a prolonged and more effective supply of active substances to the plant, increasing their bioavailability and reducing the frequency of treatments.

Secondly, it is necessary to implement omics analysis methods, such as metabolomics and proteomics, for an in-depth study of extracts. Metabolomics allows for a comprehensive analysis of the entire set of metabolites in the extract and in the plant object, helping to understand which compounds are responsible for biological activity and how they change under the influence of external factors [151]. For example, it is possible to identify which secondary metabolites in buckwheat extract are responsible for its ability to suppress weed growth, or how the composition of the extract changes with changing storage conditions [151–154]. Proteomics studies the proteins involved in plant responses to the extract, providing an understanding of the molecular mechanisms of its action [155]. These methods allow for in-depth monitoring of the action of extracts at the molecular level, identifying specific biomarkers and accurately understanding the mechanisms of their action, which is critical for optimizing the composition and effectiveness of drugs.

In addition, it is essential to create extensive databases of extracted bioactivity by donor plant species, target pathogens, and crops. These databases should contain information on the chemical composition of extracts, their effectiveness against specific diseases and pests, optimal dosages, and application conditions for different crops. Such centralized resources will greatly facilitate the selection of the most effective solutions for specific agricultural problems, make the use of extracts more predictable and scientifically substantiated, and facilitate their widespread adoption.

Conclusion

In conclusion, plant extracts are a versatile and multifunctional tool with great potential to regulate, protect, and stimulate, thereby enhancing crop sustainability and productivity. They could significantly transform crop production methods, especially within sustainable agrisystems, providing environmentally friendly and effective solutions amidst the rising demand for safe products. However, to fully realize and utilize the potential of plant extracts, further standardization of production and application methods, comprehensive interdisciplinary research to understand their mechanisms of action, and integration with digital precision farming technologies are essential. Only through this holistic approach can we shift from empirical use to scientifically grounded and highly effective application, securing food supply and supporting sustainable agricultural development for the future.

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M.K. – concept and supervision of the work, writing the text; **E.D. –** selection of sources and writing the text; **E.B. –** writing and editing the article text.

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Conflicts of Interest

The authors declare no conflicts of interest.

Compliance with ethical standards

This article does not contain a description of studies performed by the authors involving people or using animals as objects.

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Ауыл шаруашылығы дақылдарының өнімділігі мен тұрақтылығының индукторлары ретінде өсімдік тектес сығындыларды пайдалану перспективалары

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Аңдатпа. Қазіргі уақытта заманауи ауыл шаруашылығы экономикалық өнім көлемінің төмендеуі және экологиялық жағдайдың нашарлауы аясында өнімділіктің тұрақты өсуін талап етеді. Перспективті бағыттардың бірі – дәстүрлі агрохимиялық препараттарға балама табу. Өсімдік сығындылары – екіншілік метаболиттердің әртүрлілігіне байланысты көп функционалды артықшылықтарды ұсынатын перспективалы шешім. Бұл шолуда сығындылардың химиялық құрамы мен өндіру әдістері, соның ішінде дәстүрлі мацерация/перколяция және ыстыққа сезімтал қосылыстар үшін жылдамырақ әдістер талқыланады. Жасушалардың бөлінуін ынталандыру, стресске байланысты гендерді модуляциялау, ризосфера микробиотасын ынталандыру арқылы минералды қоректенуді жақсарту, фотосинтетикалық тиімділікті арттыру, фитогормондарға әсері сияқты сығындылардың фитостимуляциялық және биостимуляциялық әсерлеріне ерекше назар аударылады. Микробқа қарсы және аллелопатикалық қасиеттері де талқыланады. Биохимиялық тұрақсыздық, мөлшерлеу мәселелері және стандартталған хаттамалардың жоқтығы сияқты негізгі мәселелер атап өтілген. Шешімдер ұсынылған, оның ішінде тұжырымдалған өнімдерді әзірлеу, омикалық талдауды пайдалану және деректер қорын құру. Сондай-ақ сығындылардың толық әлеуетін ашу үшін одан әрі стандарттауды және цифрлық технологиялармен интеграцияны қажет ететін тұрақты ауылшаруашылық жүйелеріне арналған жан-жақты құрал екендігі атап өтіледі.

Түйін сөздер: Өсімдік сығындылары, биостимуляторлар, фитопстимуляторлар, аллелопатикалық эффект, тұрақты ауыл шаруашылығы, екіншілік метаболиттер

Перспективы использования растительных экстрактов в качестве стимуляторов продуктивности и устойчивости сельскохозяйственных культур

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Аннотация. В настоящее время современное сельское хозяйство на фоне снижения экономического производства и ухудшения условий окружающей среды, нуждается в устойчивом росте производительности. Одним из перспективных направлений является поиск альтернатив традиционным агрохимикатам. Растительные экстракты перспективных многообещающим решением, предлагающим многофункциональные преимущества благодаря разнообразию вторичных метаболитов. В данном обзоре обсуждается химический состав экстрактов и методы производства, включая традиционную мацерацию/перколяцию и более быстрые методы для термочувствительных соединений. Особое внимание уделяется фитостимулирующим и биостимулирующим эффектам экстрактов, таким как стимулирование деления клеток, модуляция генов, связанных со стрессом, улучшение минерального питания путем стимуляции микробиоты ризосферы, повышение эффективности фотосинтеза и влияние на фитогормоны. Также рассматриваются антимикробные и аллелопатические свойства. Освещены основные проблемы, такие как биохимическая нестабильность, проблемы дозирования и отсутствие стандартизированных протоколов. Предлагаются решения, включая разработку формулированных продуктов, использование омикс анализов и создание баз данных. В заключение подчеркивается, что экстракты являются универсальными инструментами для систем устойчивого земледелия, требующими дальнейшей стандартизации и интеграции с цифровыми технологиями для раскрытия их полного потенциала.

Ключевые слова: Растительные экстракты, биостимуляторы, фитостимуляторы, аллелопатические эффекты, устойчивое сельское хозяйство, вторичные метаболиты

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