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Review Article

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Role of Nano-based Plant Growth Regulators in Enhancing Essential Oil Yield and Agronomic Performance of Basil (Ocimum basilicum)

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Abstract: The application of nanotechnology in agriculture has introduced nano-fertilizers as sustainable and efficient alternatives to conventional chemical inputs. Among these, nano-structured plant growth regulators (PGRs) have shown great promise due to their enhanced bioavailability, targeted delivery, and reduced environmental toxicity. These nanomaterials not only improve soil nutrient dynamics but also significantly influence plant physiology, leading to improved growth, stress resistance, and enhanced phytochemical profiles. Specifically, nano-enabled PGRs have improved the yield and composition of essential oils in the cultivation of aromatic and therapeutic plants like *Ocimum basilicum* (basil). Basil is widely valued for its therapeutic properties and is a key species in the essential oil industry. The effects of several nano-structured PGRs on basil development have been studied using randomized complete block design (RCBD), with essential oil profiling conducted using gas chromatography–mass spectrometry (GC-MS). Significant differences between treatments have been confirmed by statistical techniques such as ANOVA and Tukey's post hoc test. This review synthesizes current research on the use of nano-PGRs in basil, emphasizing their potential to enhance both agronomic performance and secondary metabolite production. The findings support the integration of nanotechnology into sustainable agricultural practices, particularly in high-value crops where essential oil quality and yield are critical.

Keywords: Nano fertilizers, Plant growth regulators, Basil (Ocimum basilicum), Essential oil yield, Nanocarriers, Sustainable agriculture, GC-MS analysis.

1. Introduction

Agriculture is one of the most significant sectors of the global economy, producing the greatest food resources and serving as the main engine of the economies of the majority of nations. By 2030, the agriculture sector is expected to generate US$ 2.9 trillion in global investment [1]. In spite of numerous obstacles, such as fungi, insects, weeds, herbivorous, phytopathogenic and other pests, as well as abiotic stresses brought on by climate change, the use of agrochemicals, such as fertilizers, pesticides and plant growth regulators, is crucial for boosting agricultural output [2]. Fertilizers play an important role in agriculture they not solely provide macro-nutrients and micro-nutrients to crops but additionally increase crop yield. Fertilizer are utilized to provide potassium phosphorous and nitrogen to the plant [3]. Agrochemicals are used extensively around the world; each year, about 2.5 million tons of pesticides are consumed [4, 5]. However, unselective application of agrochemical can contaminate the environment and endanger non-target organisms (humans, soil microbiota, native fauna, and flora) as well as pest resistance [1]. Figure 1. depicts the role of pesticides in environmental contamination.

Nanotechnology features a vast potential to aid agriculture, creating the agriculture industry a lot of environment friendly with its current annual rate of growth of 25% (US$ 1.08 billion) [7]. Nanoparticles are typically created to increase product solubility, protect bioactive ingredients from premature degradation, or provide a controlled release method for agrochemicals [8].

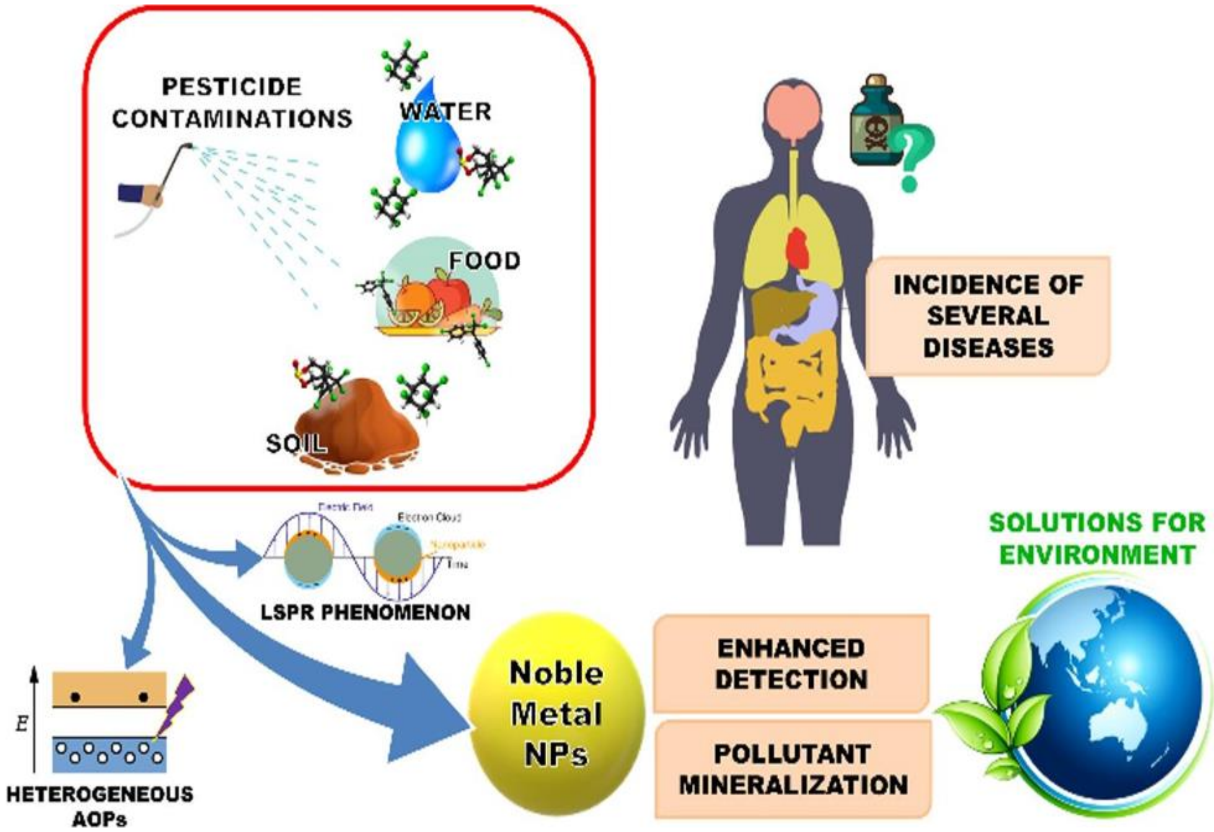

Figure 1. A visual schematic showing the impact of pesticides and the application of nanotechnology in environmental contexts [6]

Because they reduce the risk of environmental contamination and, consequently, the toxicity to humans and other non-target creatures, nanoparticles may improve the efficacy of agrochemicals, yielding better results with lower dosages and a wider variety of uses [9, 10].

The capacity of nanotechnology to be used to a wide range of applications has garnered attention and helps to increase agricultural sustainability [11-14]. In nanotechnology, two main techniques are used. In the "bottom-up" method, structures and instruments are made from element of molecule that is chemically assembled according to the concepts of recognition of molecule. Nano-objects in 'top-down' method are erected from larger components lacking atomic level power [7]. Generally, nanoparticles are made with the aim that provide an organized unleash method for agrochemicals, increasing the products solubility or defending the biologically active compounds in contrast to early degradation [8].

It contributes to lowering the levels of agrochemicals utilized in the industry while simultaneously improving the yield and quality of crops [15]. High soil quality, less water contamination, and less risk to users and agricultural workers are further characteristics. In addition to their many potential uses, nanoparticulate systems are frequently employed for loading bioactive substances as an extra environmentally friendly substitute for conventional techniques. These technologies increase the bioavailability at the organism being observed, encourage prolonged release and deliver active compounds to the appropriate targets [16]. Nanoparticulate systems have the ability to increase biological activity and decrease the toxicity of insecticides, fungicides and herbicides in agricultural applications [5, 17, 18]. However, research must be conducted to determine the impact of these technologies on human health and the environment before they are used. Although some nanocarrier systems have been found to be employed with plant growth regulators (Table 1), all of these systems indirectly help to extend production once they are used for the control of pests and other insects.

A class of substances known as plant growth regulators (PGRs) plays crucial roles. The application of these plant hormones, or chemicals that change plant hormonal homeostasis and signaling, to crops can promote plant growth, boost yield, enhance food's nutritional value and appearance, and lengthen storage or shelf life [19].

Table 1. Commonly Used Nanomaterials in Nano-PGR Formulations and Their Roles in Plant Growth

Nanomaterial	Chemical Composition	Function in Plant System	Advantages
Nano-Silver (AgNPs)	Silver nanoparticles	Antimicrobial action, enhances nutrient uptake	Disease resistance, improved growth
Nano-Zinc (ZnO NPs)	Zinc oxide nanoparticles	Enzyme activation, chlorophyll synthesis	Stimulates photosynthesis, increases yield
Nano-Iron (Fe_3O_4 NPs)	Magnetite nanoparticles	Chlorophyll production, electron transport	Enhances vegetative growth
Nano-Copper (CuO NPs)	Copper oxide nanoparticles	Lignin biosynthesis, reproductive growth	Increases resistance to pathogens
Nano-Titanium (TiO_2 NPs)	Titanium dioxide nanoparticles	Light absorption, photosynthetic efficiency	Boosts biomass and growth under low light
Chitosan NPs	Biopolymer-based nanoparticles	Growth stimulation, stress protection	Biodegradable, eco-friendly, acts as PGR and pesticide
Silicon NPs	Amorphous silicon-based nanoparticles	Strengthens plant structure, drought resistance	Enhances resilience to abiotic stress
Nano-Hydroxyapatite	$Ca_5(PO_4)_3(OH)$	Phosphorus source, root stimulation	Slow-release fertilizer, enhances root length

Gibberellic acid (GA3), one of the PGRs most widely utilized for a range of crops, is one example [20]. For example, it can be used to overcome seed dormancy by morphological and physiological mechanisms. Gibberellins promote the production of hydrolases, particularly α-amylases, which allow the embryo to access the endosperm stores [21]. Plant growth regulators have an impact on the quantity of essential oil storage structures, plant development, and essential oil biosynthesis, all of which can change the amount of essential oil produced [22]. Plant growth regulators regulate the growth of plants as well as the production of their main and secondary metabolites. Plant growth regulators can be used to improve the quality and content of essential oil in aromatic plants including peppermint, lemongrass and rose-scented geranium [23]. Growth regulators have been used in agriculture since 1940 to regulate developmental processes such as germination, postharvest senescence, vegetative growth, maturation, and reproduction [24]. Despite being used in agriculture for many years, little is known about how growth regulators affect the generation of secondary metabolites [25].

Essential oils are utilized in the food and pharmaceutical industries because of their medicinal, antibacterial, and antioxidant properties. In addition, because of their biological properties, essential oils can be employed as insecticides, herbicides and anticancer agents [9, 10]. The main component of basil *(Ocimum basilicum)* cultivars was (-)-linalool (up to 71%) with other components being (-)-bornyl acetate, (-)-camphor, a-humulene, eucalyptol, eugenol, (-)-Trans-caryophyllene, a-trans-bergamotene and cadinol.

2. Fertilizer

Globally one of the important factor is fertilization that increase the efficiency of recovered product in agriculture activities. Annual fertilizer consumption in Pakistan, US, and Brazil for nitrogen is 63% consumed. Fertilizers play an important role in agriculture they not solely provide macro-nutrients and micro-nutrients to crops but additionally increase crop yield. Fertilizer are utilized to provide potassium phosphorous and nitrogen to the plant [3]. The worldwide usage and utilization of agro-chemicals is approximately 2500000 tons of pesticides expended per annum [4]. Nevertheless, the unselective agrochemicals usage can cause the ecological contamination, resulting in threats to the cell that are not targeted (humans, soil micro biota, native plants and animals) and tolerate to pest [1].

There are numerous detrimental effects of chemical fertilizers on human health. Along with humans, these heavy metals have detrimental effects on the land, soil, and water. Overuse of chemical fertilizers can have negative effects, including pollution and the greenhouse effect [2]. According to Elumalai *et al.* (2025), there was a significant rise in the use of chemical pesticides and fertilizers between 2001 and 2021, which accelerated the release of toxic substances from nitrogen-based fertilizers, including nitrous oxide (N_2O), nitric oxide (NO), and ammonia (NH_3). According to Elumalai et al., pesticide classes like organochlorines, organophosphates, and neonicotinoids pose considerable environmental hazards due to their persistence and bioaccumulation potential. These substances negatively affect soil fertility, water quality, and biodiversity, while also being linked to adverse human health outcomes. Furthermore, the authors highlighted the role of agrochemicals in exacerbating climate change by contributing to greenhouse gas emissions and disrupting weather patterns, including temperature fluctuations and rainfall anomalies as shown in Figure 2. [26].

Moreover, excessive phosphate and nitrate levels in rivers and drinking water, which result from the transportation of phosphorus fertilizer and the use of nitrogen fertilizer, are harming human health and the environment [27]. Nitrosamines and their derivatives are among the many compounds found in excessive nitrogen fertilizer use, particularly when plants like spinach and lettuce leaves are consumed. This causes a dangerous buildup of NO2 and NO3. Regrettably, more gaseous nitrogen enters the atmosphere as NH3 to upset the ecological balances of natural ecosystems and as N2O to produce greenhouse warming [28]. Additionally, chemical fertilizers contain high levels of radionuclides and heavy metals like chromium and cadmium, which can lead to numerous detrimental environmental issues [4].

3. Nano fertilizer

Numerous strategies have been developed to address the issue of fertilizer consumption and promote its economical use. Researchers around the world have worked to create nano fertilizers in an attempt to address these growing environmental and health concerns.

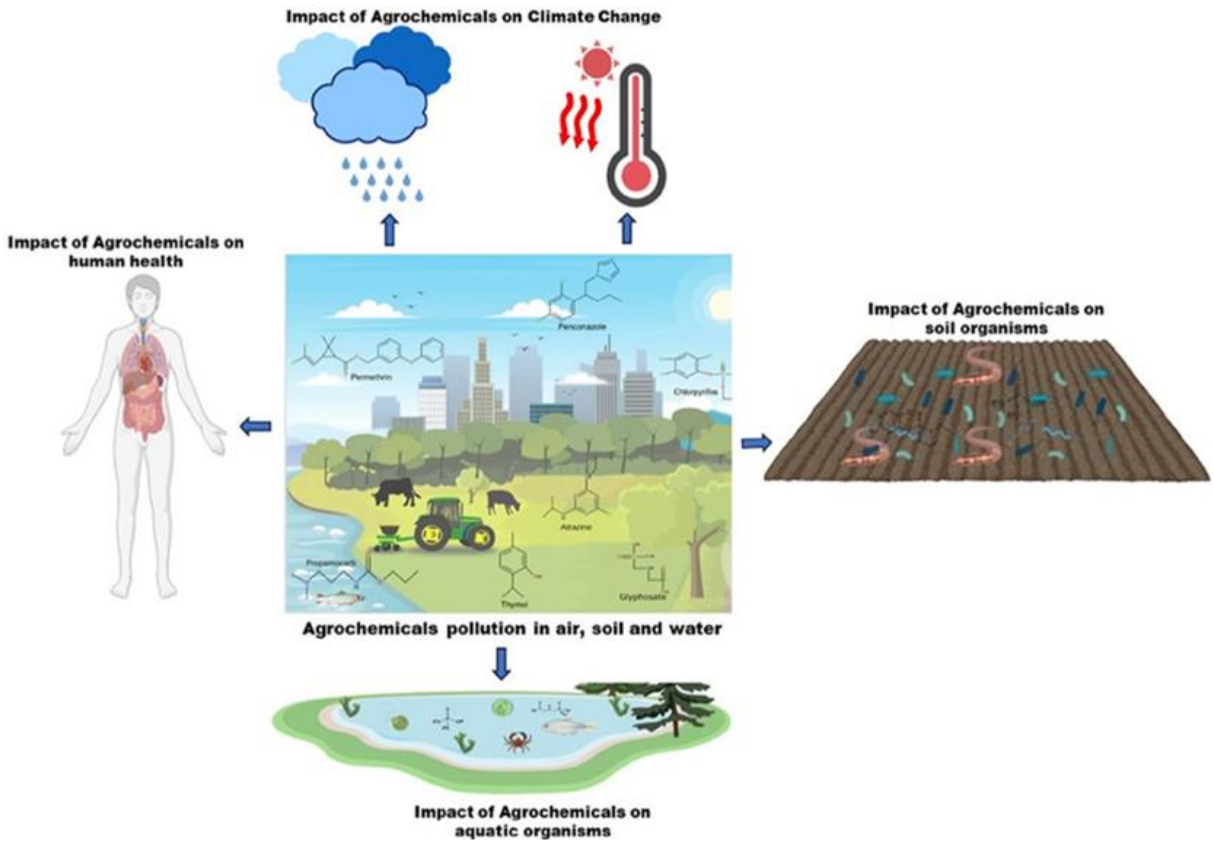

Figure 2. Impacts of Agrochemical Pollution on Ecosystem and Public Health [26]

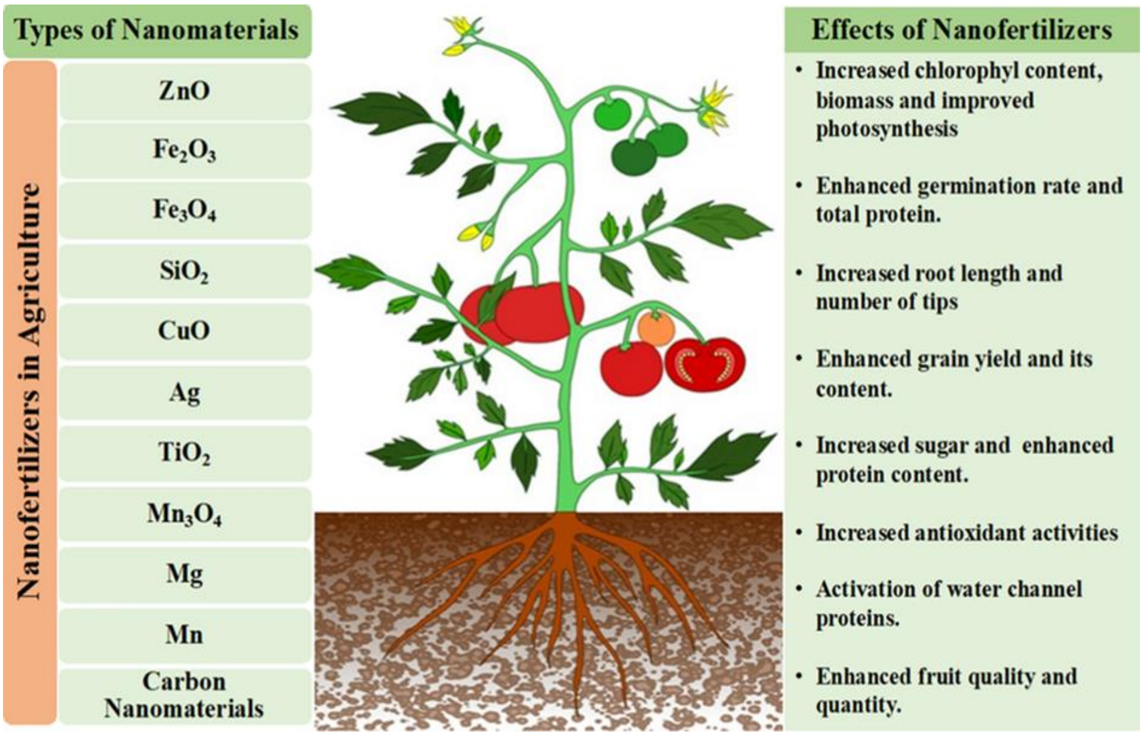

Figure 3. This figure summarizes various types of nanomaterials utilized as nanofertilizers and their diverse impacts on agricultural crops. The effects of nanofertilizers on plants vary depending on their composition and mode of action [29].

As a result, these nano fertilizers have transformed the drawbacks of conventional fertilizers and have a long-lasting effect on the environment and human health. There are several uses for nanoscience and nanotechnology in every industry, including agriculture [2]. Nanomaterials, nanopesticides, and nanofertilizers were synthesized using novel techniques that not only boost agricultural land productivity but also lessen the risk of environmental damage. An element that contains particles with at least one dimension of about 1100 nm is referred to as a nanomaterial. Because of their larger surface area, nano fertilizers, an alternative to conventional chemical fertilizers, absorb more fertilizer, preventing nutrient loss from the leaching effect. The importance of the micronutrients in nano fertilizers for plant growth and the eventual production of agricultural crops is also being studied. The application of nano-sized materials reduces the amount of fertilizer lost in the soil system due to elution and evaporation. Figure 3 illustrates the many kinds of nanomaterials used as nanofertilizers and their various effects on crops.

The diversity of the nano fertilizer ingredients helps them to maintain their identity in the soil [5]. Furthermore, nano fertilizers save water from harmful pesticides and insecticides and are reasonably priced. Nano fertilizers are crucial agricultural tools that can enhance crop growth, yield, and quality characteristics while increasing nutrient usage efficiency, decreasing fertilizer waste, and lowering cultivation costs. They give the plant more surface area for various metabolic processes, which speed up photosynthesis and increase crop yield and dry matter production. Additionally, it shields plants from many biotic and abiotic stressors. The nanomaterials known as nano-fertilizer have the potential to function as both macro and micronutrients for plants. Additionally, it facilitates the effective use of nutrients by acting as carriers of nanocarriers, which are typical chemical fertilizers [6]. The precipitation method is typically used to create nanoparticles using a fixed quantity of macro and micronutrients. Precipitation is the process by which a separable solid material separates from a solution, either by changing the solvent's composition or by turning the material into an insoluble form.

4. Growth Regulators

Plant hormones (phytohormones) are chemical compound present in plant with low concentrations [30]. Plant hormones control growth and development, defenses pathogen release stress, regulate of organ size and reproductive develop [31] (Table 2). Plant growth regulators are countless 2.5% of worldwide market for input of agriculture compounds. Plant growth regulators are used to enhance productivity and profit ability. Plant growth regulators, which have a significant impact on the terpene content and characteristics, control the growth of aromatic plants and the manufacture of terpenoids. In the 1930s, plant growth regulators were first used systematically. Presently, annual sales worldwide are over US$1.2 billion [19]. Terpenoid production relies on main metabolic processes, including photosynthesis and oxidative pathways, to provide carbon and energy. Triacontanol, a naturally occurring plant growth regulator, is crucial for boosting biomass production, which in turn improves secondary product biosynthesis.

Gibberellic acid (GA3), a phytohormone, was used to examine physiological changes in plants, including photosynthesis, flowering, development, and cell expansion. The use of GA3 leads in pressure and anthocyanin production, which improves metabolic movement within pathways. Phytohormones or plant development controllers are dynamic at low focus and have a particular effect on plant development. Auxin, cytokinin, gibberellins, abscisic corrosive, and ethylene are examples of plant development controllers; jasmonate and brassinosteroids are sometimes thought of as such. Auxin, gibberellin, cytokinin, abscisic corrosive, ethylene, and brassinosteroids are all examples of plant development controllers (phytohormones) that have been used to improve physiological and biochemical parameters, which directly affect the terpenoid pathway. As a result, essential oil's qualities and quantity were enhanced.

Development has essential in the life of any living being and it is normally controlled or regulated by at least one variable, either inner (inside the life form) or outer (its condition). In plants, these variables are achieved through the activity of some chemical operators called hormones. They are activating specialists or substances since they start a biochemical procedure which eventually prompts development. These procedures incorporate development of leaves, stems, blossoms, roots and different qualities of the plant. A portion of these substances are additionally combined by man so they are for the most part alluded to as plant development substances. Plant growth regulator or substance (PGRs) assume fundamental jobs in a vegetation's from torpidity to senescence; in this way they are significant in agribusiness, agriculture and different regions where plant development is basic.

Table 2. Classification of plant growth Hormones based on their function and origin.

Hormone Group	Examples	Natural Source	Primary Function
Auxins	Indole-3-acetic acid (IAA)	Shoot and root apices, seeds	Cell elongation, apical dominance, root initiation
Cytokinins	Zeatin, Kinetin	Roots, developing embryos	Cell division, delay of senescence, shoot initiation
Gibberellins	GA_1, GA_3, GA_4	Young leaves, seeds, root tips	Stem elongation, seed germination, flowering
Abscisic Acid (ABA)	Abscisic acid	Mature leaves, roots	Stress response, stomatal closure, seed dormancy
Ethylene	Ethylene gas	Ripening fruits, senescing leaves	Fruit ripening, leaf abscission, flower senescence
Brassinosteroids	Brassinolide, Castasterone	Pollen, seeds, leaves	Cell elongation, vascular differentiation
Salicylic Acid (SA)	Salicylic acid	Leaves, phloem tissue	Defense signaling, thermogenesis
Jasmonates (JA)	Jasmonic acid, Methyl jasmonate	Wounded tissues, chloroplasts	Wound response, herbivory defense, reproductive development

A portion of the indistinct biosynthetic pathways of these substances ought to likewise be explained so as to augment their latent capacity.

5. Effect of Plant Growth Regulators on Essential Oil Production in Aromatic Plants

Organic substances known as plant growth regulators (PGRs) have the ability to improve, suppress or alter physiological processes in plants, even at low concentrations. Their significance in agriculture was first recognized in the early 20th century, and since then, they have played a crucial role in manipulating plant development. PGRs act differently depending on the plant species, plant part, concentration applied, environmental conditions, and interactions with other regulators. These compounds are involved in the initiation, growth, and differentiation of tissues and organs and are especially important in regulating the aromatic and medicinal properties of plants. PGRs have the ability to affect essential oils' chemical makeup and yield. Applications of auxins such benzyl amino purine (BAP) and indole-3-acetic acid (IAA), for instance, have been proven to increase the amount of essential oil in aromatic plants like basil. Gibberellic acid (GA), on the other hand, has occasionally been shown to lower essential oil concentrations. In several basil species, the relative content of key compounds such as methyl chavicol has been observed to decrease slightly with the use of certain PGRs, while compounds like eucalyptol may increase. The essential oil yield in species such as *Ocimum gratissimum* and *Ocimum basilicum* varies based on the region and plant variety, with reported oil content being higher in some Turkish and Iranian basil varieties compared to Egyptian ones. Moreover, in species like *Cymbopogon citratus* and *C. jwarancusa*, specific regulators like chlormequat and gibberellic acid have been effective in enhancing the citral and overall oil yield. While IAA and kinetin may reduce vegetative growth in basil, they can still positively influence essential oil quality and profile [32, 33].

5.1. Gibberellic Acid (GA_3)

Gibberellic acid significantly affects both the structure and yield of essential oil in aromatic plants. Its application has been linked to a marked decline in certain major constituents. For instance, a substantial reduction in methyl chavicol content—falling by more than 58%—has been recorded, resulting in its concentration decreasing to 70.6% of its original level. Conversely, trans-anethole exhibited a notable increase, reaching approximately 12.3%. Gibberellic acid treatment has also been linked to the removal of some volatile chemicals, such azulene and β-cedrene, and the appearance of other ones, like ledene, juniper camphor, naphthalene and germacrene-D. Other pre-existing compounds showed significant variation; cadiene content increased more than fourfold, cubenol levels rose approximately elevenfold, and dendrene concentrations increased by over six times.

While GA_3-treated plants typically exhibit lower essential oil yields, those treated with kinetin and ethephon tend to maintain yields comparable to control plants. The reduction in oil yield following GA_3 application is attributed to the nature of gibberellins, which are diterpenes that interfere with gene expression related to their own biosynthesis and degradation. Specifically, GA_3 tends to suppress the expression of GA20-oxidase and GA3-oxidase biosynthetic genes, while enhancing the expression of GA2-oxidase, which is involved in gibberellin deactivation.

5.2. Indole-3-Acetic Acid (IAA) and 6-Benzylaminopurine (BAP)

Root initiation, bud development, and cell expansion are all facilitated by auxins like IAA, which are important regulators of plant growth and development. Together with cytokinins such as BAP, they aid in coordinating flowering and organogenesis. IAA is the most prevalent auxin found in nature, and it is mostly produced in the apical areas of roots and shoots. It exists in both free and conjugated forms and is actively transported within plant tissues.

Methyl chavicol slightly increased and trans-anethole slightly decreased when IAA was applied to basil, but other major essential oil components only slightly changed. Furthermore, several changes in composition were observed, including the emergence of germacrene-D and the lack of aristolene. Similarly, BAP treatment produced results consistent with IAA, with the primary exception being the disappearance of aromadendrene.

5.3. Methyl Jasmonate

Methyl jasmonate (MeJA) has been shown to significantly enhance monoterpene production in basil. Plants treated with MeJA demonstrated higher levels of linalool and eugenol compared to untreated controls, with increases of approximately 43% and 56%, respectively. These changes are thought to result from the upregulation of genes involved in the phenylpropanoid and terpenoid biosynthesis pathways. Although the specific enzymatic activities related to monoterpenoid synthesis have not been fully characterized, it is evident that MeJA influences gene transcription and boosts the formation of key aroma compounds. Volatile organic compounds such as β-ocimene and linalool are notably increased following MeJA application.

5.4. Salicylic Acid

Salicylic acid has demonstrated positive effects on both basil (*Ocimum basilicum*) and marjoram (*Majorana hortensis*) under controlled conditions. At specific concentrations, it enhances biomass production, photosynthetic pigment levels, carbohydrate content, amino acid profiles, and essential micronutrient concentrations. In basil, salicylic acid at a concentration of 10^{-4} M has been shown to increase essential oil yield and improve oil quality by raising eugenol content and enhancing antioxidant potential. Major oil constituents under all treatment conditions included α-cadinol, linalool, 1,8-cineole, methyl eugenol, and eugenol.

Moreover, salicylic acid pretreatment has been found to alleviate the negative physiological effects of salinity stress in basil, including reduced germination rates and biomass. It mitigates these impacts by improving ion balance, reducing lipid peroxidation, and enhancing overall stress tolerance.

5.5 Kinetin

Kinetin application has been associated with improved vegetative growth and increased essential oil content in basil. Compared to control plants, those treated with kinetin displayed higher values for parameters such as plant height, number of branches, internode length, and total leaf area. While IAA-treated plants showed moderate improvement, GA_3 had a stronger effect on vegetative growth but tended to reduce essential oil concentration. Kinetin treatments resulted in higher oil yields than either GA_3 or control, although specific essential oil components such as linalool showed limited response. Compounds like borneol and methyl chavicol declined slightly, while secondary constituents including limonene, methyl anthranilate, and geraniol exhibited modest increases.

5.6 Oxalic Acid

Oxalic acid (OA) has been explored for its potential to enhance postharvest quality in perishable crops. It functions as an antioxidant and anti-browning agent, preserving bioactive compounds during cold storage. In fruits such as pomegranate, banana, and mango, OA application has been shown to reduce chilling injury, delay ripening, suppress ethylene production, and maintain antioxidant capacity. Pre-storage dipping of mango in OA, for instance, slowed deterioration and prolonged shelf life under ambient conditions.

5.7 Sodium Nitrophenolate

Sodium nitrophenolate is a mixture of three nitrophenolate salts and is known for its solubility and bioactivity. It enhances plant resistance to diseases and pests when applied with other agrochemicals. It is also used to promote vigorous plant growth and stress tolerance at recommended application rates (e.g., 6 mL per liter of solution).

5.8 Ethephon

Ethephon is commonly used to regulate fruit ripening, promote synchronized boll opening, and enhance defoliation efficiency. It functions by breaking down into ethylene, which is a natural ripening hormone. Ethephon has been applied successfully to improve seed germination and accelerate harvesting schedules in various crops.

5.9 Tetcyclacis

Tetcyclacis, a norbornenodiazetine-based plant growth retardant, is known to suppress shoot elongation by inhibiting sterol biosynthesis. Its application leads to an increase in cholesterol content while reducing other sterol compounds such as campesterol and sitosterol. In basil and other species like sunflower, soybean, and maize, tetcyclacis has been shown to reduce shoot growth, particularly in younger tissues. This suppression effect diminishes as plants mature but remains most pronounced in newly developed organs.

5.10 Methodology

There is various method used to extract the essential oil from basil (*Ocimum basilicum*) plant. Hydro distillation (HD), Stem distillation (SD), Solvent free method extract etc. are the most economical processes. Due to presence of volatile compounds hydro distillation and steam distillation are best techniques for extraction of essential oil from basil (*Ocimum basilicum*) plant. Hydro distillation is commonly used in laboratory while steam distillation is used for commercial scale. The chemical profile of the basil essential oil separated by solvent free method extract (SFME) and hydro distillation (HD) in reserchers study was similar to that reported by Figueredo et al. [34]. Prashant M. et al. reported that essential oil extracted from *Zingiber purpureum* Roxb. (commonly known as Bangle) holds considerable potential for development and utilization. Their study examined how variations in the feed-to-solvent ratio (F/S = 0.2, 0.3, and 0.4 g/mL), rhizome particle size (0.5 cm and 2 cm), and extraction technique (specifically hydrodistillation) impact both the yield and quality of the essential oil. The outcomes demonstrated that: (i) an F/S ratio of 0.3 g/mL yielded the most efficient oil recovery; (ii) smaller rhizome pieces (0.5 cm) led to higher extraction efficiency; and (iii) hydrodistillation was effective in producing oil with a higher content of terpinene-4-ol, the major bioactive compound, as confirmed by GC-MS analysis as shown in Figure 4. [35].

Essential oil of basil has been traditionally extract from complete above-ground herbage using steam distillation [36]. The components of basil essential oil identified by GC and GC-MS using both techniques. Both SFME and HD isolates of basil leaves have the same main constituents in their essential oil. Monoterpene, sesquiterpene and derivatives of phenylpropanoid chemicals were identified among 65 combinations in basil essential oil, which accounted for 99.3% and 99.0% of the total oil obtained by solvent free method extract (SFME) and hydro distillation (HD), respectively. The primary constituents of the essential oil are monoterpenes. However, the two extraction techniques have different absolute amounts. The most prevalent oxygenated molecule in basil essential oil is linalool, a monoterpene alcohol (43.5% for SFME and 48.4% for HD).

5.11 Basil

Basil is the oldest species belonging to the *Ocimum genus* and related to Lamiaceae (Labiatae) family [37]. About 200 species are occur in *Ocimum genus* with different forms and botanic varieties. Common named of *Ocimum basilicum* such as sweet basil, and it is a popular culinary herb. *Ocimum basilicum* initially native to Indian and other Asian countries it is also called rehan in Arabic and known as slahbeq in Algeria. Currently it is cultivated in whole the world [38].

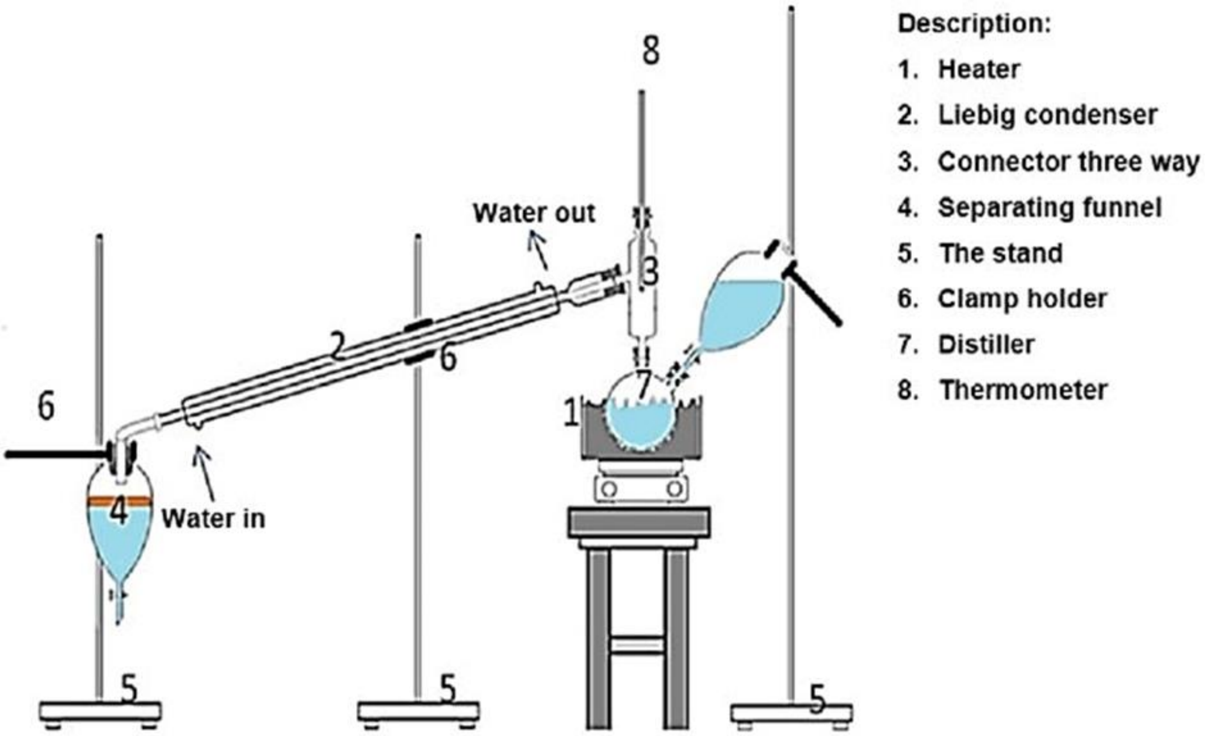

Figure 4. Extraction of Essential Oil from Bangle (Zingiber purpureum Roxb.) using Hydrodistillation Technique [35]

Basil oil acquired by refining from dry herb, is one of the segments of scent creations applied in aroma industry.

The basil herb contains up to 1.5% of essential oil in the arrangement of which the most valuable mixes are linalool and eugenol. Sweet basil (*Ocimum basilicum L.)* is the most broadly developed basil species on the world for the new market or for basic oil creation. *Ocimum basilicum* species is viewed as promising essential oil crops in the south eastern United States; in any case, look into on oil creation and synthesis of these species in Mississippi and the south eastern United States is inadequate.

Ocimum basilicum (basil) has a rich cultural and medicinal heritage that extends far beyond its well-known culinary use. Historical records suggest that basil was employed in ancient Egypt for its preservative and embalming properties, as evidenced by its presence in tombs and mummies. In ancient Greece, basil symbolized mourning and reverence, often referred to as *basilikon phuton*, meaning "royal" or "sacred plant." Similarly, in traditional Indian systems of medicine such as Ayurveda, basil has been widely used for its therapeutic effects in managing various ailments. Over time, the applications of basil have evolved, and it continues to hold relevance in multiple domains. Beyond food seasoning, basil is now used in the formulation of perfumes, incense, and various holistic remedies. Recent scientific investigations have confirmed that basil essential oils contain bioactive compounds with strong antioxidant, antibacterial, and antiviral activities. These properties support its continued use in both traditional and modern medicinal systems. Plants like basil are recognized as vital sources of phytochemicals and antioxidant nutrients. In modern agriculture, enhancing the productivity and phytochemical content of medicinal plants like basil has become a priority. The strategic use of agrochemicals, including plant growth regulators, fertilizers, and pesticides, plays a crucial role in overcoming numerous biotic and abiotic stresses such as fungal infections, insect attacks, herbivory, weed competition, and climate-induced challenges. As research advances, the integration of such practices with sustainable and precision farming techniques is essential for improving both the yield and quality of high-value crops like basil. [2].

Basil is a well-known culinary herb and its essential oils have been utilized widely for a long time in the enhancing of confectionary and baked goods fixings (e.g., ketchups, pickles, tomato paste and vinegars), wieners and meats, serving of mixed greens dressings, nonalcoholic refreshments, frozen yogurt, and frosts. Basil oil has additionally discovered a wide application in perfumery, just as in dental and oral items. It is likewise utilized in fragrance-based treatment. Basil has a built up antibacterial activit

Additionally, it has been shown that extracted essential oils contain naturally occurring components with antibacterial, fungistatic, insecticidal, and nematoidal effects. These characteristics are frequently attributed to the predominant elements of essential oils, such as methyl chavicol, camphor, methyl cinnamate, eugenol and linalool. The main constituent of the essential oil found in the basil (Ocimum basilicum) plant is linalool.

5.12 Comparative Analysis: Nano vs. Conventional PGRs in Basil

The use of plant growth regulators (PGRs) in agriculture has significantly improved crop productivity. However, conventional PGRs often suffer from low bioavailability, rapid degradation, and non-targeted delivery. In contrast, nano-based PGRs (nano-PGRs) offer superior efficiency due to their nanoscale size and high surface area, which enhance plant absorption and cellular uptake. Nano-PGRs can penetrate the plant cuticle more efficiently and are often encapsulated or coated to provide sustained release, reducing the frequency of applications. This precision delivery results in improved physiological responses in basil, such as better shoot elongation, earlier flowering, and higher biomass accumulation. Moreover, studies have demonstrated that nano-formulations can significantly boost the biosynthesis of essential oils by enhancing metabolic pathways and enzyme activity outcomes not always achieved with conventional PGRs. In terms of efficacy, nano-PGRs have shown more pronounced effects even at lower concentrations compared to traditional formulations, indicating reduced input requirements and cost-effectiveness in the long term.

5.13 Environmental and Agronomic Benefits of Nano-PGRs

Nano-based PGRs present several environmental and agronomic advantages over conventional counterparts (Table 3). The controlled release and targeted delivery mechanisms reduce the likelihood of off-target effects and environmental contamination.

Table 3. Comparative Impact of Conventional PGRs and Nano-PGRs on Basil (Ocimum basilicum) Growth Parameters

Growth Parameter	Control (No PGRs)	Conventional PGRs	Nano-PGRs	% Increase by Nano-PGRs over Control
Plant Height (cm)	22.4 ± 1.3	28.1 ± 1.1	32.7 ± 0.9	+46%
Number of Leaves	45 ± 3	60 ± 4	75 ± 2	+66%
Leaf Area (cm²)	12.3 ± 0.6	16.7 ± 0.8	21.1 ± 0.7	+71%
Fresh Biomass (g)	8.2 ± 0.4	10.5 ± 0.5	13.9 ± 0.6	+69%
Dry Biomass (g)	2.1 ± 0.2	3.0 ± 0.2	3.8 ± 0.1	+81%
Essential Oil Yield (%)	0.75 ± 0.05	0.89 ± 0.03	1.16 ± 0.04	+54%
Chlorophyll Content	Low	Moderate	High	Significantly enhanced

Lower doses are needed to achieve the same or better responses, thereby minimizing chemical runoff into surrounding ecosystems. From an agronomic standpoint, nano-PGRs can improve the resilience of basil plants against abiotic stresses such as drought, salinity, and temperature extremes. Their ability to enhance nutrient uptake and metabolic activity further contributes to improved crop health and productivity. Additionally, their use aligns with sustainable agricultural practices by reducing the total agrochemical load, enhancing input efficiency, and contributing to food safety and security goals through reduced residues in edible plant parts.

5.14 Challenges and Future Prospects

Despite the promising outcomes, several challenges still limit the widespread adoption of nano-PGRs. One major concern is the potential toxicity of nanoparticles to non-target organisms, including beneficial soil microbes and pollinators. Long-term studies are lacking on the fate, persistence, and accumulation of nanoparticles in the environment and food chains. Regulatory frameworks for nano-agrochemicals are still evolving, and the absence of standardized protocols for risk assessment hinders their commercialization. There is also a need for cost-effective large-scale production techniques for nano-PGRs that maintain consistency in size, composition, and stability. Future research should focus on green synthesis methods, biodegradable nanocarriers, and the integration of nano-PGRs with other sustainable technologies such as precision farming. Comprehensive field trials, environmental impact studies, and policy development will be critical to ensuring the safe and effective use of nano-PGRs in basil and other economically important crops.

6. Conclusion

The integration of nanotechnology into agriculture presents a transformative shift in how we approach crop production, pest management, and soil fertility. Conventional chemical fertilizers and plant growth regulators (PGRs), while crucial for enhancing crop yield and addressing biotic and abiotic stresses, pose significant environmental and health risks due to their excessive and unregulated usage. The emergence of nano fertilizers and nano-enabled PGRs offers a more sustainable and efficient alternative by improving nutrient uptake, reducing chemical runoff, and enhancing the bioavailability of active compounds. This review highlights how nano fertilizers contribute to better nutrient delivery, reduced environmental contamination, and increased crop productivity. Similarly, the application of plant growth regulators in nano-form enhances not only plant growth and development but also boosts essential oil yield and composition in medicinal and aromatic plants such as basil (*Ocimum basilicum*). With its rich profile of bioactive compounds—particularly linalool—basil stands out as a model plant to study the synergistic effects of nano-fertilizers and nano-PGRs on essential oil biosynthesis. Furthermore, the selection of appropriate extraction methods such as hydro-distillation and steam distillation plays a vital role in maintaining the quality and yield of essential oils. However, for these advancements to be successfully implemented at scale, further environmental risk assessments, long-term safety studies, and regulatory frameworks are essential to ensure their safe usage.

In conclusion, nano-enabled agricultural technologies hold great promise in promoting sustainable practices, improving essential oil quality, and addressing the limitations of conventional agrochemicals. Their strategic application in crops like basil could revolutionize agricultural outputs while safeguarding environmental and human health

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Conflict of interest

The Authors declares that there is no conflict of interest anywhere.

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