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Review

Effect of Nanoparticles on the Content, Yield, and Component Composition of Essential Oils from Medicinal and Aromatic Plants: A Review of Experimental Studies

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Abstract

The review summarizes experimental data on the effect of nanoparticles on the formation of essential oils in medicinal and aromatic plants. Eighty-five unique experimental publications were included in the tabulated evidence, and the data were summarized in three tables devoted to the effects of nanoparticles on essential oil content, yield, and component composition. Nanoparticles often increased essential oil content and yield, with the strength of the effect depending on species, chemotype, and growing conditions, as well as on nanoparticle chemical composition, size, concentration, and application method. The concentration–response relationship was almost always non-linear, and changes in essential oil content were not always proportional to changes in oil yield. The most pronounced effects were characteristic of nanoparticles that can simultaneously act as a source of a mineral element and as an abiotic elicitor. Combined use of different nanomaterials often produced additive effects. Nanoparticles of different chemical nature frequently produced similar shifts in the relative proportions of secondary metabolites, whereas closely related plant species could respond differently to the same nanoparticle preparation. Comparisons with ionic and bulk materials did not confirm a universal advantage of the nanoform. Therefore, the practical value should be demonstrated separately for each nanoparticle–plant system. The review outlines limitations and prospects for crop production.

Keywords: nanoelicitation; secondary metabolism; phytotoxicity; foliar application; terpenoid biosynthesis

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1. Introduction

Essential oils are of particular importance among the products of secondary metabolism; they determine the characteristic aromatic properties of many plant species. Essential oils are multicomponent volatile products of natural origin, which are extracted from plant material mainly by steam distillation. In terms of their chemical composition, they are multicomponent mixtures that include monoterpene and sesquiterpene hydrocarbons, phenylpropanoids, and other volatile compounds [1]. The chemical diversity of essential oils determines the wide range of their practical applications. In perfumery and cosmetics,

essential oils are primarily used as aromatic ingredients [2]. In the food industry, the antimicrobial and antioxidant properties of essential oils are used to extend shelf life, including in coatings and active packaging [3–5]. For agricultural needs, the insecticidal, repellent, and antifungal activity of certain essential oils and their derivatives is of great interest [6–9]. In medicine, biologically active components based on essential oils are used to manufacture pharmacological preparations. Thus, 1,8-cineole is used as an adjunct to standard therapy for bronchial asthma [10] and chronic obstructive pulmonary disease [11], while eugenol is used as part of zinc oxide–eugenol dental materials [12]. At the same time, the biological properties of essential oils are determined not only by the presence of individual active compounds but also by the overall composition of the oil, as well as the quantitative ratio of the components that make it up. The interaction between the main and minor components of essential oils can be additive, synergistic, or antagonistic in nature, and the observed effect depends on the composition of the mixture, the concentrations of individual substances, and the biological model used [13].

The content and component composition of essential oils often depend on the genetic characteristics of the plant, its stage of development, and growing conditions [14,15]. If we consider a broader range of factors, differences in the composition of essential oils may also be related to the variety and chemotype, the studied organ, the age of the plant, the developmental phase, light exposure, temperature, water availability, and mineral nutrition. Additional variability is introduced by the timing of harvesting and the conditions for processing the raw material. For *Thymus hyemalis* Lange and *Thymus vulgaris* L., for example, significant seasonal changes in the component composition of the essential oil have been demonstrated [16]. The dependence of essential oil accumulation on the phenological phase has been established for most essential oil crops, including *Ocimum basilicum* L. [17], *Origanum vulgare* L. [18], *Thymus vulgaris* L. [19], *Lavandula angustifolia* Mill. [20]. The most favorable time for harvesting raw materials for processing is usually the beginning of the flowering phase. Using *L. angustifolia* Mill. as an example, it was shown that the accumulation of essential oils depended not only on the stage of flower development but also on weather conditions [21]. Thus, even for a single species, the quantitative and qualitative characteristics of essential oils can vary significantly depending on the stage of plant development and the conditions under which they are grown and harvested. At the same time, the dependence of secondary metabolism on environmental factors should be considered not only as a source of natural variability in the composition of essential oils, but also as an opportunity for targeted regulation of their accumulation and component composition under artificial conditions. In particular, it has been shown that moderate exposure to abiotic stress factors can alter the biosynthesis of essential oils and the ratio of individual components [22].

The approach of elicitation is based on the use of stress responses of plants to stimuli—targeted exposure to biotic or abiotic factors that activate protective and signaling processes that can change the intensity of secondary metabolism [23,24]. Biotic elicitors, physical effects, including ultraviolet radiation, as well as exogenous signaling compounds, in particular salicylic acid and methyl jasmonate, are used for this purpose [25]. For medicinal and aromatic plants, it has been shown that such effects can alter both the accumulation of volatile compounds and the component composition of essential oils [26]. In recent years, various nanoparticles (NPs) have been actively used as abiotic elicitors. Today, the effects of nanoparticles with the chemical composition ZnO, CuO, various iron oxides, TiO_2, SiO_2, Se, and some other nanoparticles on plants have been studied [27–30]. The effectiveness of using nanoparticles is often determined by their chemical composition, size, concentration, surface properties, electrokinetic potential, and solubility in the medium. For example, with foliar application, it is important how well the nanoparticles adhere to the

surface and whether they are capable of penetrating into the tissues. When nanoparticles are applied to the root zone, their entry into the plant depends on the interaction with the components of the medium and the root surface [31]. The schematic process of the influence of nanoparticles on the level of accumulation and composition of essential oils is presented in Figure 1. For materials containing nutrients essential for plants, such as zinc, iron, or copper, changes in the availability of these elements may occur, including due to the dissolution of particles. Another possible process is a change in the redox state of cells, caused by the additional generation of reactive oxygen species (ROS). ROS are involved in the transmission of stress signals and affect the calcium and hormonal regulation of secondary metabolism [24]. The generation of ROS when nanoparticles enter the plant organism is considered one of the proposed mechanisms underlying elicitation [32]. Data on transcriptional changes have been obtained for individual plants. Thus, after treating *Mentha* × *piperita* L. with TiO_2 nanoparticles, an increase in the expression level of genes related to monoterpene metabolism was recorded [33]. The increase in essential oil yield caused by nanoparticles is often associated with changes in the growth rate and photosynthetic parameters of plants. For example, in *Vetiveria zizanioides* (L.) Nash, when treated with TiO_2 nanoparticles at a concentration of 90 mg L^{-1}, the essential oil content and yield increased by 22.6% and 55.1%, respectively, while the chlorophyll content and the maximum photochemical efficiency of photosystem II also increased [34]. In another study, in *M.* × *piperita*, the combination of methyl jasmonate at a concentration of 0.1 mM with TiO_2 nanoparticles at a concentration of 150 mg L^{-1} increased the proportion of menthol in the essential oil by approximately 45% [35]. However, the stimulating effect of nanoparticles may be replaced by growth inhibition, reduced photosynthetic activity, and other signs of phytotoxicity as their concentration increases [27,28]. At the same time, the concentration that is optimal for plant growth does not necessarily ensure the maximum accumulation of essential oils. Thus, in *Tanacetum parthenium* (L.) Sch.Bip., treatment with ZnO NPs at a concentration of 1000 parts per million (ppm) increased the essential oil content from 0.56 to 0.90% (volume/weight, *v*/*w*), i.e., by approximately 61% compared to the control. At the same time, the maximum dry biomass of the plants was observed at a higher concentration—2000 ppm [36]. A similar dose-dependent effect was observed when plants were treated with TiO_2 NPs: the maximum positive effect on the content and component composition of essential oils was observed at a concentration of 1500 ppm, and on biomass growth at 2000 ppm [37]. Therefore, for the practical cultivation of essential oil crops, it is necessary to take into account at least three independent indicators: essential oil content, essential oil yield, and the component composition of the essential oil. The yield of essential oil is a particularly important agronomic indicator, as it depends both on the oil concentration in the raw material and on the biomass.

Today, there are quite a number of review articles devoted to the use of nanomaterials in crop production, including their impact on secondary metabolism [38–45], while information about the effect of nanoparticles on the content, yield, and qualitative composition of essential oils remains fragmented and rudimentary. The following key questions remain unanswered: does an increase in essential oil content due to the action of nanoparticles lead to an increase in the essential oil yield, and how does the component composition change in this process? Do nanoforms have advantages over ionic and bulk forms of the corresponding substances? In this review, these questions are considered together for various plant species and types of nanomaterials. This approach makes it possible to assess changes in the content, yield, and composition of essential oils, identify recurring patterns, and determine the limitations for the practical application of nanomaterials. In this regard, the aim of this review is to systematize experimental data on the effect of nanoparticles and nano-fertilizers on the content, yield, and component composition of essential oils of

medicinal and aromatic plants. Special attention is paid to the type and size of nanoparticles, as well as their concentration and method of application.

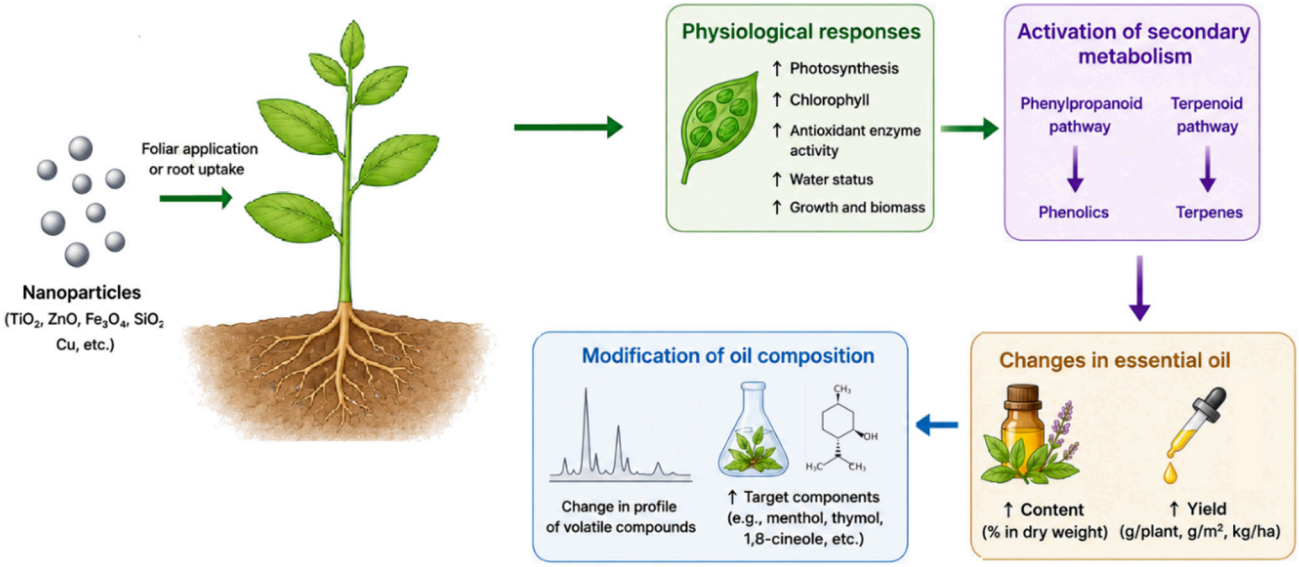

Figure 1. Schematic representation of the proposed mechanisms by which nanoparticles affect essential oil content, yield, and composition in plants. Arrows linking these responses represent hypothesized relationships rather than universally established causal mechanisms.

2. Methodology for Searching and Selecting Publications

The search for scientific publications was carried out in the electronic databases Google Scholar, Scopus, Web of Science and PubMed. In addition, we used searches by DOI, the reference lists of the found articles, and the "cited by" and "related articles" functions. The last search was conducted on 10 July 2026. The following combinations of keywords in English were used for the search: nanoparticles; nanofertilizer; nano-fertilizer; metal nanoparticles; metal oxide nanoparticles; essential oil; volatile compounds; secondary metabolites; medicinal plants; aromatic plants; Lamiaceae; *Mentha*; *Salvia*; *Lavandula*; *Origanum*; *Satureja*; *Dracocephalum*; *Nigella*; *Thymus*; *Rosmarinus*. In some cases, the search was conducted using the names of individual nanomaterials: TiO_2 nanoparticles; ZnO nanoparticles; Cu nanoparticles; Fe nanoparticles; Fe_2O_3 nanoparticles; CeO_2 nanoparticles; Ag nanoparticles; chitosan nanoparticles.

The review included experimental studies that examined the effect of nanoparticles or nanofertilizers on medicinal and aromatic plants, and also presented data on the essential oil content, the essential oil yield, or changes in the composition of volatile components, which were primarily determined using gas chromatography–mass spectrometry (GC–MS). Additionally, we took into account studies where nanoparticles affected individual components of essential oil or terpene secondary metabolites, such as menthol, menthone, thymol, carvacrol, linalool, 1,8-cineole, geranial, neral, camphor, and other compounds.

Review articles, publications without experimental data, studies not related to plant objects, works that did not use nanoparticles or nanomaterials, as well as articles in which only growth or physiological indicators were assessed without determining the content, yield, or component composition of essential oil and other volatile secondary metabolites, were excluded from the analysis. In addition, studies devoted to clonal micropropagation, in vitro experiments, and biotechnological approaches were not taken into account. Review articles were used exclusively to search for additional primary literature sources and to clarify the presumed mechanisms of action of nanoparticles. The search was conducted sequentially, using various combinations of the listed keywords, plant names, and nano-

materials. Identical entries were identified and removed manually based on matching the DOI; if it was not available, they were identified by the publication title, authors, and year of publication. Each unique publication was counted once, with different experimental variants from the same publication listed as separate lines in the tables.

As a result, 85 unique experimental publications were included in Supplementary Tables S1–S3, comprising 193 rows: 69 on essential oil content, 53 on yield, and 71 on composition. These tables contain 64, 53, and 69 unique publications, respectively; some publications contribute to more than one table.

The influence of a wide variety of factors on the accumulation of essential oils makes a full comparison and analysis of the experimental publications difficult, so the interpretation of the data is provided with significant limitations and takes into account only the main and primary parameters (plant species, location of the experiment, elemental composition of the nanoparticles, nanoparticle size, and type of nanoparticle application). Due to the high heterogeneity of the experimental designs, types of nanoparticles, units of measurement for oil yield, and growing conditions, a -scale quantitative meta-analysis was not conducted; the results were summarized primarily at a qualitative level, with recurring patterns identified.

Since various units of measurement were used in the initial studies, the original values and units of measurement were, whenever possible, converted to a single format. The essential oil content was determined as the amount of oil per unit of mass of plant material and was expressed in % (by volume) or % (by mass), with the mass indicated as fresh (FW) or dry (DW). The essential oil yield was determined for each plant, pot, plot, square meter, or hectare. The values were not converted from fresh mass to dry mass or from units of measurement tied to the plant to units of measurement tied to the area, except in cases where the necessary data on moisture content, biomass, planting density, or plot size were available. Relative changes were calculated within each experiment using the corresponding control values.

Quantitative summary indicators were used only to assess the relative changes in essential oil yield, as presented in Figure 2. Figure 2 includes 190 treatment–control comparisons from 53 unique publications in Table S2. Each plotted comparison was treated as a separate descriptive observation, not as independent evidence. The relative change was calculated as the difference between the value after treatment and the value in the corresponding control, divided by the value in the control and multiplied by 100%. Within each nanomaterial group, the median relative change was first calculated for each contributing publication; the group summary is the median and interquartile range of these publication-specific medians. A publication may contribute to more than one group, so the group-specific publication counts are not additive. This analysis did not take into account weighting coefficients and was purely descriptive in nature. Results for which $\Delta > 0$ were classified as positive, $\Delta < 0$ as negative, and $\Delta = 0$ as no change. Cases in which the original publication explicitly stated the absence of changes were also classified as "no change." Statistical significance was not used as a classification criterion, as this indicator was not provided in all studies included in the review. Accordingly, the terms "positive" and "negative" describe the numerical direction of change relative to the control and do not imply statistical significance or reproducibility.

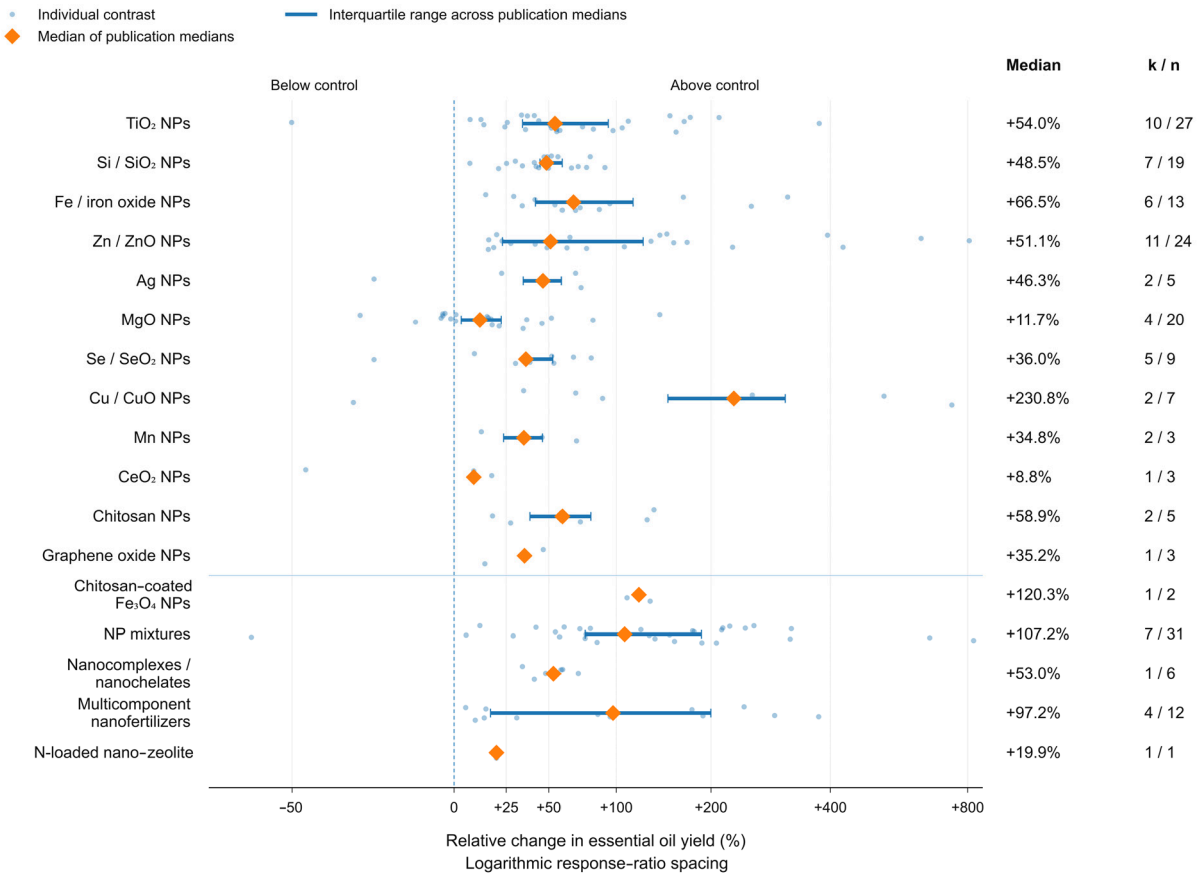

Figure 2. The effect of various nanomaterials on the yield of essential oils: a summary of the literature data. Blue dots indicate individual comparisons (with NPs/control). Orange diamonds indicate the median of publication-specific medians; horizontal lines indicate the interquartile range (IQR) of these values (25th–75th percentiles). For each group, n denotes the number of comparisons and k denotes the number of contributing publications. The vertical dashed line indicates no change relative to the control. The figure presents an unweighted descriptive summary of 190 comparisons from 53 unique publications in Table S2. A publication may contribute to several groups.

2.1. Assessment of the Quality of the Studies Included

The methodological quality of the primary experimental studies was assessed using four groups of criteria: (1) characterization of nanomaterials and application methods; (2) experimental design and control treatments (ionic, bulk, positive controls, etc.); (3) methods for essential oil extraction and calculation of its content and yield; and (4) methods for determining the composition of essential oils.

2.1.1. Characterization of Nanomaterials and Application Methods

We examined whether the origin of the nanomaterial or its synthesis method was reported. We also checked for results from electron microscopy (TEM/HRTEM, SEM), X-ray diffraction (XRD), dynamic light scattering (DLS), ζ-potential measurements, and other methods. For concentrations expressed in mM, we determined the basis of the calculation. Molarity values for heterogeneous nanomaterials were noted as a limitation when the calculation method was not explained.

2.1.2. Experimental Design and Control Treatments

We checked whether the plant species, cultivar or chemotype, plant organ studied, developmental stage, growing conditions, and timing of material collection were reported.

We also checked for the use of a randomized block design. Particular attention was paid to the inclusion of appropriate controls: where solvents, surfactants, stabilizers, or carriers were used, we checked whether controls containing the same additives were included. For experiments involving combined treatments, we assessed whether it was possible to distinguish the effects of the nanomaterial from those of fertilizers, growth regulators, microorganisms, and other components.

2.1.3. Methods for Essential Oil Extraction and Calculation of Its Content and Yield

We checked whether the source plant material, its condition (fresh or dried), and the method and duration of oil extraction were described. We also checked whether the oil content per unit mass of raw material and the total oil yield per plant or per unit area had been calculated, and whether these values were consistent.

2.1.4. Determination of Oil Composition

We assessed whether GC–MS or GC–FID data were available. We checked whether the criteria for compound identification and the methods used for quantitative calculation were reported. We also examined whether mass-spectrum library matches were corroborated by experimentally determined retention indices calculated relative to a series of *n*-alkanes. Identification based solely on mass-spectrum library matches, without additional confirmation, was recorded as a limitation. The use of reference standards, internal standards, and response correction factors was also considered.

2.1.5. Recording Limitations in the Selection of Literature Sources

For each group of criteria, we recorded whether there were no substantial concerns, insufficient methodological detail, or a substantial methodological deficiency. A complete absence of information for any criterion was considered a limitation. No overall quality score was calculated: decisions about the use of data were made in light of the nature of the deficiency and its effect on the specific conclusion. The absence of any single nanomaterial characterization method was not, in itself, grounds for excluding a study.

Studies with incomplete methodological descriptions were retained if the data allowed the relevant result to be interpreted, while taking the reported limitations into account. Results from the combined application of a nanomaterial and other components were included in the descriptive synthesis as effects of the treatment as a whole, without attributing the effect to the nanomaterial alone.

The identified limitations were recorded concisely in Tables 1–3 and in full in Tables S1–S3.

3. The Effect of Nanoparticles on Essential Oil Content

Growing essential -bearing and medicinal plants in controlled agriculture solves the problem of optimizing the use of arable land; however, the plants obtained in this way have significantly lower essential oil content (up to 10 times less) [46]. To increase the rate of essential oil accumulation, the spectral composition of the lighting is mainly selected [47], including the use of additional light treatments of plants with ultraviolet radiation [48], as well as the application of additional nutrients or -inducing substances [26,49] that can stimulate the production of secondary metabolites, which include essential oils. The use of nanomaterials as elicitors is a very promising direction for increasing the productivity of essential oil crops [28]. Table 1 (and Table S1) summarizes experimental data on the effect of metallic, metal oxide, -containing, carbon, and biopolymer nanomaterials, as well as complex nano fertilizers, on the essential oil content of medicinal and aromatic plants. In most of the studies under consideration, nanoparticles increased the concentration of

essential oil in plant material; however, the magnitude of the effect varied significantly between plant species and depended on the chemical composition, size, and concentration of the nanomaterial, the method of its application, and the conditions under which the experiment was conducted.

Since the studies used different parts of the plants, extraction methods, measurement bases, and units of measurement, the initial indicators of essential oil content were presented as in the original publications. Cross-study comparison was based on the relative change from the corresponding control.

Table 1. Effects of nanoparticle treatments on essential oil content in medicinal and aromatic plants.

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Content	Notes/EO Basis	Limitations	Ref.
Ocimum basilicum L.	Fe_2O_3 NPs + ZnO NPs	50	Foliar spray: Fe_2O_3: 0, 50, 100 mg L^{-1} × ZnO: 0, 25, 50 mg L^{-1}.	Field experiment	control: 1.00%; Fe_2O_3 100 mg L^{-1}: 1.41% = +41.0%; ZnO 25 mg L^{-1}: 1.12% = +12.0%; Fe_2O_3 100 mg L^{-1} + ZnO 25 mg L^{-1}: 1.80% = +80.0%; Fe_2O_3 100 mg L^{-1} + ZnO 50 mg L^{-1}: 1.23% = +23.0%;	Best effect: Fe_2O_3 100 mg L^{-1} + ZnO 25 mg L^{-1}: 1.80% = +80.0%; / Shoots dried at 40 °C; DW basis.	Commercial nanoparticles are used (they are not characterized in the study). The properties of the working suspension are not described. Ionic or bulk controls are absent. The essential oil content is reported by the authors, but the detailed calculation procedure is not disclosed.	[50]
Pelargonium graveolens L'Hér.	Fe_3O_4 NPs	≈12.6	Foliar spray: 0, 5, 10 mg L^{-1};	Field experiment;	Control: 0.132%; 5 mg L^{-1}: ≈0.248% = ≈+87.9%; 10 mg L^{-1}: ≈0.270% = ≈+104.5%	Higher EO content at 10 mg L^{-1} among NP-only treatments. / Air-dried material	Incomplete characterization of the nanoparticles: DLS, ζ-potential, and XRD are not reported. The concentration of the ionic control is not equivalent to the nanoparticle concentration.	[51]
Foeniculum vulgare Mill.	TiO_2 NPs/bulk TiO_2	NPs ≈ 21; Bulk ≈ 1933	Foliar spray: 0, 0.1 and 0.2 mM	Greenhouse pot experiment	Control: 0.90%; TiO_2 NPs: 0.1 mM: 1.70% = +88.9%; 0.2 mM: 1.40% = +55.6%; Bulk TiO_2: 0.1 mM: 1.10% = +22.2%; 0.2 mM: 1.30% = +44.4%.	Best effect: TiO_2 NPs, labelled 0.1 mM (1.70%; +88.9%). / % (*w*/*w*), DW; dried fruits	Incomplete characterization of the nanoparticles: XRD are not reported. There are inconsistencies in the reported nanoparticle concentrations.	[52]
Lavandula angustifolia Mill.	GO NPs	–	Foliar spray: 0, 12, 25, 50 mg L^{-1}	Field experiment	control: ≈0.32%; 12 mg L^{-1}: ≈0.35% = +9.4%; 25 mg L^{-1}: ≈0.38% = +18.8%; 50 mg L^{-1}: ≈0.42% = +31.3%	Best effect: 50 mg L^{-1} =+31.3% / % (*w*/*w*), DW; dried foliage.	Incomplete characterization of the nanoparticles: DLS and ζ-potential are not reported. Ionic or bulk controls are absent.	[53]
Dracocephalum kotschyi Boiss.	Se NPs/sodium selenite (SSe)	12–30	Foliar spray: Se NPs: 50, 100, 200 mg L^{-1}; SSe: 50, 100, 200 mg L^{-1}	Greenhouse experiment	control: 1.60%. Se NPs: 50 mg L^{-1}—1.35% = −16%; 100 mg L^{-1}—2.30% = +44%; 200 mg L^{-1}—1.40% = −13%. SSe: 50 mg L^{-1}—1.20% = −25%; 100 mg L^{-1}—1.80% = +13%; 200 mg L^{-1}—1.25% = −22%.	Best effect: 100 mg L^{-1} Se NPs = +44%. / % (*w*/*w*), DW; dried leaves.	Incomplete characterization of the nanoparticles: DLS, ζ-potential, and XRD are not reported. Dose equivalence across treatments in terms of elemental Se is not specified. The calculation of essential oil yield is insufficiently substantiated.	[54]

Table 1. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Content	Notes/EO Basis	Limitations	Ref.
Cymbopogon flexuosus (Nees ex Steud.) W.Watson	SiO_2 NPs Aerosil R812	-	Foliar spray: 50, 100, 150, 200 mg L^{-1}	Green-house/pot	control: ≈0.47%. SiO_2 NPs: 50 mg L^{-1}—≈0.53%, = +13%; 100 mg L^{-1}—≈0.57%, = +22%; 150 mg L^{-1}—≈0.64%, = +35%; 200 mg L^{-1}—≈0.60%, = +28%.	Optimum 150 mg L^{-1} SiO_2 NPs. / Gravimetric; FW/DW NR; hydrodistillation.	The contributions of the solvent and nanoparticles are insufficiently substantiated. The method used to analyze the essential oil composition is not described in sufficient detail.	[55]
Mentha × *piperita* L.	TiO_2 NPs	<21	Foliar spray: 0, 50, 100, 150, 200, 250 mg L^{-1}	Pot experiment; 150 DAP	control: ≈0.66%; TiO_2 NPs: 50 mg L^{-1} ≈0.68% = +3%; 100 mg L^{-1} ≈0.76% = +15%; 150 mg L^{-1} ≈0.92% = +39.4%; 200 mg L^{-1} ≈0.84% = +27.2%; 250 mg L^{-1} ≈0.80% = +21%	Optimum 150 mg L^{-1} TiO_2 NPs; after 150 mg L^{-1}, the effect begins to diminish. / Hydrodistillation (3 h); gravimetric determination as reported by the authors; fresh- or dry-weight basis not explicitly specified.	Incomplete characterization of the nanoparticles: XRD and TEM are not reported. Ionic or bulk controls are absent. The method used to determine the essential oil composition is not described in sufficient detail.	[56]
Salvia officinalis L.	TiO_2 NPs	10–15	Foliar spray: 0, 10, 50, 100, 200, 1000 mg L^{-1}	Greenhouse experiment	control: 0.16%; TiO_2 NPs: 10 mg L^{-1} 0.18% = +12.5%; 50 mg L^{-1} 0.23% = +43.8%; 100 mg L^{-1} 0.25% = +56.3%; 200 mg L^{-1} 0.28% = +75.0%; 1000 mg L^{-1} 0.22% = +37.5%	Best effect: 200 mg L^{-1}. / %, air-dried shoots; *w*/*w* or *v*/*w* NR.	The essential oil content is described inaccurately and insufficiently transparently.	[57]
Ocimum tenuiflorum L.	SiO_2 NPs (Si) + TiO_2 NPs (Ti)	5.2–12.1 + 10.2–15.2	Foliar spray; Si50 + Ti50; Si100 + Ti50; Si100 + Ti100; Si200 + Ti100; Si100 + Ti200; Si200 + Ti200 mg L^{-1}	Pot/net-house experiment	control: ≈0.11%; Si50 + Ti50 ≈0.14%, = +27%; Si100 + Ti50 ≈0.27%, = +145%; Si100 + Ti100 ≈0.30%, = +172.4%; Si200 + Ti100 ≈0.28%, = +155%; Si100 + Ti200 ≈0.13%, = +18%; Si200 + Ti200 ≈0.07%, = −36%	Optimum Si100+Ti100 mg L^{-1} / Gravimetric, FW; fresh leaves; hydrodistillation.	Commercial nanoparticles were used. The working suspension is incompletely characterized: DLS, ζ-potential, and XRD are not reported. Ionic or bulk controls are absent. The method used to determine the essential oil composition is not described in sufficient detail. The main EO experiment included combined SiO_2 NP and TiO_2 NP treatments and a water control; corresponding single-material EO treatments were not reported in the main experiment.	[58]

Table 1. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Content	Notes/EO Basis	Limitations	Ref.
Pelargonium graveolens L'Hér.	Ag NPs	5–35	Foliar spraying; 0, 20, 40 and 80 mg L^{-1}	Greenhouse experiment	control: 1.29%; 20 mg L^{-1}—1.74% = +34.9%; 40 mg L^{-1}—1.45% = +12.4%; 80 mg L^{-1}—1.84% = +42.6%.	Best effect: Ag NPs 80 mg L^{-1}. / %, air-dried aerial parts; *w*/*w* or *v*/*w* NR.	Commercial nanoparticles are used and are incompletely characterized: DLS, ζ-potential, and XRD are not reported. Ionic or bulk controls are absent.	[59]
Dracocephalum kotschyi Boiss.	CeO_2 NPs/ bulk CeO_2	10–30	Foliar spray; 0, 50, 100, 200 mg L^{-1}	Greenhouse experiment	control: ≈1.44%. CeO_2 NPs: 50 mg L^{-1} ≈2.15% = +49.3%; 100 mg L^{-1} 2.25% = +56.3%; 200 mg L^{-1} ≈1.66% = +15.3%. Bulk CeO_2: 50 mg L^{-1} ≈1.64% = +13.9% 100 mg L^{-1} ≈1.36% = −5.6%; 200 mg L^{-1} 2.43% = +68.8%	Best effect: bulk CeO_2 200 mg L^{-1} / % (*w*/*w*), DW; dried leaves.	Commercial nanoparticles are used and are incompletely characterized: DLS and XRD are not reported.	[60]
Matricaria chamomilla L.	Chitosan nanoparticles (CS NPs)	–	Foliar spray: 0, 100, 200, 300, 400 mg L^{-1}	Field experiment	2018/2019 control: ≈0.49%; 100 mg L^{-1} ≈0.56% = +14.3%; 200 mg L^{-1} ≈0.68% = +38.8%; 300 mg L^{-1} ≈0.77% = +57.1%; 400 mg L^{-1} ≈0.75% = +53.1%. 2019/2020: control: ≈0.51%; 100 mg L^{-1} ≈0.58% = +13.7%; 200 mg L^{-1} ≈0.66% = +29.4%; 300 mg L^{-1} ≈0.75% = +47.1%; 400 mg L^{-1} ≈0.74% = +45.1%	The best effect in both seasons: CS NPs 300 mg L^{-1} / % (*v*/*w*); air-dried flowers.	The nanomaterial is not characterized at all; only the synthesis method is described.	[61]
Ocimum basilicum L.	Fe-amino acid complexes: n[$Fe(Arg)_3$], n[$Fe(Gly)_3$], n[$Fe(His)_3$]	5–20	Foliar application; 2000 mg L^{-1} (0.2% *w*/*v*);	Greenhouse experiment	control: 0.29%; n[$Fe(Arg)_3$] 0.2%: 0.51% = +75.9%; n[$Fe(Gly)_3$] 0.2%: 0.43% = +48.3%; n[$Fe(His)_3$] 0.2%: 0.53% = +82.8% Fe-EDDHA 0.2%: 0.39% = +34.5%	Best effect: n[$Fe(His)_3$] 2000 mg L^{-1} (0.2% *w*/*v*): 0.53%, +82.8%. / % (*w*/*w*), DW; shade-dried herb.	Incomplete characterization of the nanoparticles: DLS and ζ-potential are not reported. Amino acid controls are absent.	[62]

Table 1. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Content	Notes/EO Basis	Limitations	Ref.
Ocimum basilicum L.	MgO NPs/$MgSO_4$/MgO bulk	5–20	Foliar spray: 75, 200, 300, 600 mg L^{-1};	Pot/net-house experiment	Content in DW: control 0.389%; 75 mg L^{-1}—0.440% = +13.1%; 200 mg L^{-1}—0.466% = +19.8%; 300 mg L^{-1}—0.451% = +15.9%; 600 mg L^{-1}—0.626% = +60.9%; $MgSO_4$—0.364% = −6.4%; bulk MgO—0.247% = −36.5%	Best effect: 600 mg L^{-1}: +60.9% / Volatile fraction: %, DW; hexane/GC-FID.	Incomplete characterization of the nanoparticles: XRD is not reported. The concentration of the ionic control is not equivalent to that of the nanoparticles. Essential oil content was determined by hexane extraction rather than standard hydrodistillation.	[63]
Ocimum basilicum L.	MgO NPs	6–7	Foliar spray: 0, 25, 50, 75, 100, 150, 200, 500 mg L^{-1}	Pot/net-house experiment	Contents in FW: control 0.0185%; 25 mg L^{-1}—0.0231% = +24.9%; 50 mg L^{-1}— 0.0389% = +110.3%; 75 mg L^{-1}—0.0235% =+27.0%; 100 mg L^{-1}— 0.0160% =−13.5%; 150 mg L^{-1}— 0.0138%= −25.4%; 200 mg L^{-1}— 0.0214% = +15.7%; 500 mg L^{-1}— 0.0171% = −7.6%	Best effect: 50 mg L^{-1}: +110.3%. / Volatile fraction: % (*w*/*w*), FW; hexane/GC-FID.	Incomplete characterization of the nanoparticles: XRD is not reported. Ionic or bulk controls are absent. Essential oil content was determined by hexane extraction rather than standard hydrodistillation.	[46]
Artemisia annua L. cv. Novichok	Se NPs/Na_2SeO_4	~100	Foliar spray: Se NPs: 0.39 mM = 30.6 mg L^{-1}; Na_2SeO_4: 0.39 mM = 73.2 mg L^{-1}	Field experiment	control: 0.790%; Na_2SeO_4: 0.775% = −1.9%; Se NPs: 0.355% = −55.1%	The data for two seasons have been averaged. / %, DW; *w*/*w* or *v*/*w* NR.	Incomplete characterization of the nanoparticles: XRD is not reported. Essential oil content was determined by hexane extraction rather than standard hydrodistillation.	[64]
Cannabis sativa L.	Si NPs	–	Foliar spray: 0, 0.5, 1.5 mM.	Pot/net-house experiment	control: 0.08%; 0.5 mM: 0.11% = +37.5%; 1.5 mM: 0.12% = +50.0%	Both Si NP concentrations had a positive effect. / %, dried inflorescences; *w*/*w* or *v*/*w* NR.	Nanoparticle characterization is entirely absent. A Tween 20 control without nanoparticles is not described.	[65]

Table 1. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Content	Notes/EO Basis	Limitations	Ref.
Dracocephalum moldavica L.	ZnO NPs/conventional zinc suspension (Kingfol Zinc)	10–30/–	Foliar spray: 0, 40, 80, 160, 400 mg L^{-1};	Field experiment	ZnO NPs, control: ≈0.053%; 40 mg L^{-1} ≈0.105% = +98.1%; 80 mg L^{-1} ≈0.140% = +164.2%; 160 mg L^{-1} = 0.340% = +541.5%; 400 mg L^{-1} = 0.200% = +277.4%. Zn suspension control: ≈0.056%; 40 mg Zn L^{-1} ≈0.065% = +16.1%; 80 mg Zn L^{-1} ≈0.105% = +87.5%; 160 mg Zn L^{-1} = 0.190% = +239.3%; 400 mg Zn L^{-1} = 0.130% = +132.1%	Best effect: ZnO NPs 160 mg L^{-1}. / % (*w*/*w*), DW; shade-dried aerial parts.	Minor limitations	[66]
Dracocephalum moldavica L.	ZnO NPs + CuO NPs, 1:1; conventional control—Zn suspension + chelated Cu	10–30 + ≈40	Foliar co-application: 40 + 40, 80 + 80, 160 + 160 400 + 400 mg L^{-1}	Field experiment	ZnO NPs + CuO NPs: control: ≈0.0545%; 40 + 40 mg L^{-1} ≈0.1055% = +94%; 80 + 80 mg L^{-1} = 0.216% = +297%; 160 + 160 mg L^{-1} = 0.196% = +260%; 400 + 400 mg L^{-1} ≈0.136% = +149%. Zn suspension +chelated Cu: control:≈0.0545%; 40 + 40 mg L^{-1} ≈0.096% = +77%; 80 + 80 mg L^{-1} ≈0.086% = +57%; 160 + 160 mg L^{-1} ≈0.090% = +65%; 400 + 400 mg L^{-1} ≈0.056% = +2%	Best effect: 80+80 mg L^{-1}. / % (*w*/*w*), DW; shade-dried aerial parts.	Minor limitations	[67]

Table 1. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Content	Notes/EO Basis	Limitations	Ref.
Zataria multiflora Boiss.	Si NPs; Si–DA6 nanocomplex; Si–Atonik nanocomplex; Sodium silicate	≈10; ≈20.	Foliar spray: 1.5, 3.0, 6.0 mM.	Pot/net-house	control: 2.75%; Si NPs: 1.5 mM ≈3.01% = +9.5%; 3.0 mM ≈2.97% = +8.0%; 6.0 mM 3.10% = +12.7%. Si–DA6: 1.5 mM ≈3.05% = +10.9%; 3.0 mM ≈3.15% = +14.5%; 6.0 mM 3.21% = +16.7%. Si–Atonik: 1.5 mM ≈3.00% = +9.1%; 3.0 mM ≈3.11% = +13.1%; 6.0 mM 3.19% = +16.0%. Sodium silicate: 1.5 mM ≈2.69% = −2.2%; 3.0 mM ≈2.79% = +1.5%; 6.0 mM ≈2.87% = +4.4%	Best effect: Si–DA6, 6 mM: 3.21%, +16.7%. / %, DW; *w*/*w* or *v*/*w* NR.	Incomplete characterization of the nanoparticles: DLS is not reported.The basis for calculating the nanocomplex concentration in mM and dose equivalence in terms of Si are not specified.Statistical comparisons of the proportions of essential oil components are not presented.	[68]

Full dose-resolved data for all eligible studies are provided in Supplementary Table S1. Table 1 presents 20 representative experimental series selected to illustrate the major nanomaterial classes, dose–response patterns, application methods, matched ionic or bulk controls, and both stimulatory and inhibitory responses. The selection was not based solely on effect magnitude. Values denoted by the symbol «≈» are approximately determined from the graphs in the original publications; «=» indicates values provided in the publication. The relative change is calculated in comparison with the control of the corresponding experiment. NPs, nanoparticles; EO, essential oil; FW, fresh weight; DW, dry weight; NR, not reported; GO, graphene oxide; CS NPs, chitosan nanoparticles; DAP, days after planting; SSe, sodium selenite; DA6, diethylaminoethyl hexanoate; Arg, arginine; Gly, glycine; His, histidine; Fe-EDDHA, iron chelate of ethylenediamine-*N*,*N*′-bis(2-hydroxyphenylacetic acid); XRD, X-ray diffraction; DLS, dynamic light scattering; TEM, transmission electron microscopy; GC–FID, gas chromatography with flame ionization detection; *w*/*w*, mass/mass; *v*/*w*, volume/mass; *w*/*v*, mass/volume. Atonik is a sodium nitrophenolate-based plant growth regulator. Chelated Cu denotes copper supplied in chelated form. In Ref. [58], Si and Ti in treatment labels denote SiO_2 NPs and TiO_2 NPs, respectively; the numbers indicate their respective concentrations in mg L^{-1}. In Ref. [62], the prefix n in n[$Fe(Arg)_3$], n[$Fe(Gly)_3$], and n[$Fe(His)_3$] denotes the nano-complex form. In Ref. [66], zinc suspension refers to the conventional fertilizer Kingfol Zinc (Omex Agrifluid Limited, King's Lynn, UK), abbreviated as ZnS in the original study. In Ref. [66], treatment concentrations are expressed as nominal Zn concentrations.

Based on the data presented in Tables 1 and S1, several main patterns can be identified. The first pattern is that the most pronounced effect is characteristic of nanoparticles that can simultaneously act as a source of mineral elements and as an abiotic elicitor. It is likely that the combination of nutritive and signaling effects explains the strong effect of Fe_2O_3 NPs in *M.* × *piperita*, ZnO NPs in *Matricaria chamomilla*, and SiO_2 NPs in *V. zizanioides* and *Cymbopogon flexuosus* (Nees ex Steud.) W.Watson [55,69–71].

In *Pelargonium graveolens*, foliar application of Fe_3O_4 nanoparticles without humic acid increased the reported essential oil content in both cuts during two growing seasons [51]. In the first cut of 2018, the content increased from 0.132% in the water-sprayed control to approximately 0.248% and 0.270% at 5 and 10 mg L^{-1}, corresponding to increases of approximately 87.9% and 104.5%, respectively. However, the publication inconsistently specified fresh-weight and air-dry-weight bases for this indicator.

The second pattern is that an additive effect may be observed when two different nanomaterials are used in combination. The combined use of SiO_2 and TiO_2 NPs in *Coleus aromaticus* (Lour.) Spreng. and *Ocimum tenuiflorum* L. caused an additive increase in oil content [58,72].

In a field experiment with *O. basilicum*, the combined application of Fe_2O_3 NPs and ZnO NPs (50 nm in size) at concentrations of 100 mg L^{-1} and 25 mg L^{-1}, respectively, increased the essential oil content to 1.80%, 80% higher than in the control treatment (1%). When applied separately, Fe_2O_3 NPs alone (100 mg L^{-1}) increased the essential oil content to 1.41%, while ZnO NPs alone (25 mg L^{-1}) increased it to 1.12% [50].

The combination of Si100 + Ti100 mg L^{-1} increases the oil content from 0.31% and 0.29% when used separately to 0.71% when used in combination [72]. In *O. tenuiflorum*, combined application of SiO_2 NPs and TiO_2 NPs at 100 mg L^{-1} each increased EO content from approximately 0.11% in the water control to 0.30% [58]. It is likely that studying the combined effect of nanoparticles of different chemical nature is a promising direction for further research.

The third pattern is that the method of applying nanoparticles affects the final result. Foliar treatments more often provided a more pronounced increase in essential oil content

than soil application of the same nanoparticles [73]. Consequently, at the maximum dose, foliar treatment provided more than a twofold increase in oil content compared to soil application. Probably for oil accumulation, the delivery of nanoparticles directly to the metabolically active tissues of the leaf plays an important role.

The fourth pattern is that the design of most studies is as follows: low and moderate concentrations of nanomaterials stimulated the accumulation of essential oils, whereas as the concentration increased further, the strength of the effect decreased; in some publications, an increase in the concentration of nanoparticles even inhibited the accumulation of essential oils. This pattern was most consistently observed when TiO_2-, SiO_2-, ZnO-, Fe-, and Se-containing nanoparticles were used, as well as when mint, sage, dragonhead, chamomile, and vetiver plants were employed, and less frequently with a number of other crops [34,56,57]. For example, in *Salvia officinalis* L., the essential oil content increased from 0.16% in the control to 0.18%, 0.23%, 0.25%, and 0.28% at 10, 50, 100, and 200 mg L^{-1} of TiO_2 NPs, respectively, but at 1000 mg L^{-1} it decreased to 0.22%. Thus, the optimal dose of 200 mg L^{-1} provided a 75% increase, whereas a fivefold increase in the optimal concentration reduced the effect by almost half relatively [57]. In *Rosmarinus officinalis* L. the maximum oil content was recorded at approximately 2.76% when 100 ppm of TiO_2 NPs were added, compared to 1.70% in the control; when 200 and 400 ppm of TiO_2 NPs were added, the oil content was approximately 2.70% and 2.60%, respectively [74].

The fifth pattern: in studies comparing several types of nanoparticles of similar size, it has been established that the effectiveness of nanoparticles with different chemical compositions varies significantly. These comparisons suggest that chemical composition can be an important determinant of the response. However, they do not allow the independent effect of particle size to be estimated when other physicochemical properties also differ. For *V. zizanioides*, at the same dose of 50 mg L^{-1}, SiO_2 NPs were the most effective, increasing the oil content by approximately 19.4%. TiO_2- and ZnO NPs increased it only by 11.9% and 7.5%, respectively [71]. It should be noted that the positive effect was quite small for some nanomaterials. For example, chitosan nanoparticles increased the oil content in *T. vulgaris* only from 1.34% to 1.39%, which is approximately a 4% increase [75]. In *Foeniculum vulgare* Mill., the independent use of NanoMix at concentrations of 250–1000 mg L^{-1} altered the average oil content by only 1.3–4.0% [76]. At the same time, graphene oxide nanoparticles (GO NPs) in *L. angustifolia* Mill. provided a consistent increase in oil content by approximately 31.3% relative to the control [53]. Overall, nanoparticles can be considered an effective and practical tool for regulating the amount of essential oil. At the same time, it is important to remember that the effectiveness of nanoparticles depends on a very large number of factors (chemical composition, size, concentration, method of application, and so on).

4. The Effect of Nanoparticles on Essential Oil Yield

Essential oil content describes the amount of oil per unit mass of plant material, whereas total essential oil yield describes the amount obtained per plant, plot, or unit cultivated area. Total essential oil yield therefore depends on both the biomass of the harvested organ and its essential oil content. This relationship can be expressed as follows:

$$Y_{EO} = B \times \frac{C_{EO}}{100}, \quad (1)$$

where Y_{EO} is essential oil yield, B is biomass, and C_{EO} is essential oil content in plant material. An increase in the content of essential oil does not necessarily lead to an increase in the yield of essential oil, since against the background of an increase in the content of essential oils, there may be a general decrease in the biomass of the whole plant, its fruits, leaves, etc. Tables 2 and S2 systematize data on the effect of nanoparticles on the yield of essential oil

from one plant (units of area or sowing). Because the original yield units differed, total essential oil yields were recalculated, where possible. Cross-study comparison was based on the relative change from the corresponding control rather than on pooled absolute values.

Table 2 presents 20 representative experimental series selected to illustrate the major nanomaterial classes, dose–response patterns, application methods, matched ionic or bulk controls, and both stimulatory and inhibitory responses. The selection was not based solely on effect magnitude. Full dose-resolved data for all eligible studies are provided in Supplementary Table S2. The relative change is calculated compared to the control of the corresponding experiment. Notes indicate extraction material and, where reported, the biomass basis used for yield calculation. Values marked with the symbol «≈» are approximately determined from the graphs in the original publications; «=» indicates values provided by the authors. NR, not reported; NPs, nanoparticles; EO, essential oil; FW, fresh weight; DW, dry weight; GO, graphene oxide; CS NPs, chitosan nanoparticles; SSe, sodium selenite; DA6, diethylaminoethyl hexanoate; NCF, nano-chelated fertilizer; CF, chemical fertilizer; GC–FID, gas chromatography with flame ionization detection. Atonik is a sodium nitrophenolate-based plant growth regulator. Chelated Cu denotes copper supplied in chelated form. In Ref. [58], Si and Ti in treatment labels denote SiO_2 NPs and TiO_2 NPs, respectively; the numbers indicate their respective concentrations in mg L^{-1}. In Ref. [66], zinc suspension refers to the conventional fertilizer Kingfol Zinc (Omex Agrifluid Limited, King's Lynn, UK), abbreviated as ZnS in the original study. In Ref. [66], treatment concentrations are expressed as nominal Zn concentrations.

Among the 190 comparisons included in Figure 2, 97 (51.1%) showed an increase in essential oil yield of at least 20% but less than 100%, and 53 (27.9%) showed an increase of at least 100%. Dose-resolved series in Table S2 included both monotonic increases and responses that peaked at an intermediate or low tested dose. These patterns support selecting the concentration separately for each nanomaterial–plant combination; the highest tested concentration should not automatically be considered optimal.

The nonlinear relationship between the concentration of nanoparticles and essential oil yield was particularly evident when TiO_2 NPs were used. In *S. officinalis*, essential oil yield increased by 36.9, 97.2, 167.4, and 174.5% at nanoparticle concentrations of 10, 50, 100, and 200 mg L^{-1}, respectively, but at 1000 mg L^{-1}, the increase was only 7.1% [57]. In *M.* × *piperita*, the maximum effect was observed at TiO_2 NPs concentrations of 150 mg L^{-1} (+105.1%), whereas at concentrations of 200 and 250 mg L^{-1}, the effect decreased to +73.1 and +57.1%, respectively [56]. For *V. zizanioides*, the optimal concentration of TiO_2 NPs was 90 mg L^{-1}, while for *Dracocephalum moldavica* L., the maximum concentrations in different studies were 10 or 100 mg L^{-1}. Consequently, even within a single type of nanoparticle, the effective concentration significantly depends on the species and growing conditions.

Si-containing nanomaterials also predominantly increased essential oil yield. In *C. flexuosus*, the maximumessential oil yield was observed at an SiO_2 NP concentration of 150 mg L^{-1} (+90.5%), after which the effect decreased to +69.9% at 200 mg L^{-1} [55]. For *M.* × *piperita*, the optimal concentration of Si NPs was 100 mg L^{-1} (+78.9%), while at 150 and 200 mg L^{-1} the increase was +56% and +41%, respectively. In the experiment with *Satureja hortensis* L., increasing the concentration of SiO_2 NPs from 1.5 to 2.25 mM had little effect on the essential oil yield: the increase was 47.0% and 46.8%, respectively. This indicates the achievement of a plateau, at which further increase in concentration does not provide an additional production effect.

Table 2. Effects of nanoparticle treatments on essential oil yield in medicinal and aromatic plants.

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Yield	Notes/EO Basis	Limitations	Ref.
Lavandula angustifolia Mill.	GO NPs	-	Foliar spray; 0, 12, 25, 50 mg L^{-1};	Field experiment	control: ≈355 kg ha^{-1}; 12 mg L^{-1}: ≈405 kg ha^{-1} = +14.1%; 25 mg L^{-1}: ≈480 kg ha^{-1} = +35.2%; 50 mg L^{-1}: ≈520 kg ha^{-1} = +46.5%	The essential oil yield increases with increasing concentration of GO NPs up to 50 mg L^{-1}. It is unknown whether the yield will increase at higher concentrations. / Dried foliage	Inconsistency between the graphs and essential oil yield.	[53]
Matricaria chamomilla L.	Chitosan nanoparticles (CS NPs)	-	Foliar spray; 0, 100, 200, 300, 400 mg L^{-1}.	Field experiment	control: ≈0.083 mL $plant^{-1}$; 100 mg L^{-1}: ≈0.105 = +27.4%; 200 mg L^{-1}: ≈0.142 = +71.5%; 300 mg L^{-1}: ≈0.195 = +135.0%; 400 mg L^{-1}: ≈0.189 = +128.2%	Best effect: 300 mg L^{-1} / air-dried flowers	The season and the procedure used to calculate the oil yield are not described in sufficient detail.	[61]
Ocimum basilicum L.	Fe_2O_3 NPs + ZnO NPs	50 nm	Foliar spray: Fe_2O_3: 0, 50, 100 mg L^{-1} × ZnO: 0, 25, 50 mg L^{-1}.	Field experiment	Control: 0.01100 mL $plant^{-1}$; Fe_2O_3 100 mg L^{-1}: 0.02932 mL $plant^{-1}$ =+166.5%; ZnO NPs 25 mg L^{-1}: 0.01557 mL $plant^{-1}$ = +41.5%; Fe_2O_3 100 + ZnO 25 mg L^{-1}: 0.03821 mL $plant^{-1}$ = +247.4%; Fe_2O_3 100 + ZnO 50 mg L^{-1}: 0.03173 mL $plant^{-1}$ = +188.5%	Best effect: Fe_2O_3 100 + ZnO 25 mg L^{-1}: 0.03821 mL $plant^{-1}$ = +247.4%; / Shoots dried at 40 °C; DW basis.	The authors report the essential oil yield but do not provide a detailed account of how it was calculated.	[50]
Pelargonium graveolens L'Hér.	Fe_3O_4 NPs	≈12.6	Foliar spray: 0, 5, 10 mg L^{-1}	Field experiment	Control: 0.819 mL $plant^{-1}$; 5 mg L^{-1}: ≈2.92 mL $plant^{-1}$ = +256.5%; 10 mg L^{-1}: ≈3.41 mL $plant^{-1}$ = +316.4%.	Best effect: 10 mg L^{-1} among NP-only treatments. / Author-calculated yield from shoot FW and EO content	The concentration used for ionic control is not equivalent to the nanoparticle concentration.	[51]
Foeniculum vulgare Mill.	TiO_2 NPs/bulk TiO_2	NPs ≈21; Bulk ≈1933	Foliar spray: 0, 0.1 and 0.2 mM	Greenhouse pot experiment	Control: 0.060 g $plant^{-1}$; TiO_2 NPs: 0.1 mM: 0.286 g $plant^{-1}$ = +376.7%; 0.2 mM: 0.155 g $plant^{-1}$ = +158.3%; Bulk TiO_2: 0.1 mM: 0.086 g $plant^{-1}$ = +43.3%; 0.2 mM: 0.112 g $plant^{-1}$ = +86.7%.	Best effect: TiO_2 NPs, labelled 0.1 mM (0.286 g $plant^{-1}$; +376.7%). / Dried-fruit oil; converted from g per 100 plants.	There are inconsistencies in the nanoparticle concentrations.	[52]

Table 2. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Yield	Notes/EO Basis	Limitations	Ref.
Ocimum basilicum L.	Se NPs	–	Foliar spray; 0, 50, 100 mg L^{-1}	Field experiment	control: 13.5 kg ha^{-1}; 50 mg L^{-1}: 20.5 kg ha^{-1} = +51.9%; 100 mg L^{-1}: 20.7 kg ha^{-1} = +53.3%	Means across three irrigation regimes; the two Se doses did not differ significantly. / Yield derived from dry biomass and EO content.	Oil content was calculated as the average across the three irrigation regimes. Oil yield was calculated on the basis of the plant's dry biomass, without accounting for crop yield.	[77]
Dracocephalum kotschyi Boiss.	Se NPs; sodium selenite (SSe)	≈22	Foliar spray; Se NPs: 50, 100, 200 mg L^{-1}	Greenhouse experiment	control: ≈0.070 g $plant^{-1}$; Se NPs 50 mg L^{-1}: ≈0.050 = −29%; 100 mg L^{-1}: ≈0.095 = +36%; 200 mg L^{-1}: ≈0.128 = +79.65%; SSe 50 mg L^{-1}: ≈0.043 = −39%; 100 mg L^{-1}: ≈0.067 = −4%; 200 mg L^{-1}: ≈0.043 = −39%	For Se NPs at 200 mg L^{-1}, the change is +79.65%, as reported by the authors; the rest was calculated. / Derived from EO content and leaf DW.	The essential oil yield is inconsistent with the dry leaf mass and oil content.	[54]
Artemisia annua L.	Se NPs; sodium selenate (Na_2SeO_4)	–	Foliar spray; Se NPs: 13 mg L^{-1} Na_2SeO_4: 50 mg L^{-1}	Field experiment	control: ≈0.0068 mL $plant^{-1}$; Se NPs: ≈0.0113 = +66.5%; Na_2SeO_4: ≈0.0108 = +59.8%; Se NPs + Na_2SeO_4: ≈0.0153 = +126.3%	The data are averaged over two years. Despite the decrease in essential oil content, the increase in leaf biomass led to an increase in the absolute essential oil yield. / Dried leaves and florets	The methodology for calculating essential oil yield is described imprecisely.	[78]
Cymbopogon flexuosus (Steud.) Wats	SiO_2 NPs, Aerosil R812	–	Foliar spray; 0, 50, 100, 150, 200 mg L^{-1};	Semi-controlled greenhouse; pot-based experiment	control: ≈0.47 g $plant^{-1}$; 50 mg L^{-1}: ≈0.59 = +25.2%; 100 mg L^{-1}: ≈0.71 = +51.7%; 150 mg L^{-1}: ≈0.90 = +90.5%; 200 mg L^{-1}: ≈0.80 = +69.9%	Best effect: 150 mg L^{-1}.	The methodology for calculating essential oil yield is described imprecisely.	[55]

Table 2. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Yield	Notes/EO Basis	Limitations	Ref.
Zataria multiflora Boiss.	Si NPs; Si-DA6 nanocomplex; Si-Atonik nanocomplex	≈10; ≈20	Foliar spray; 1.5, 3.0, 6.0 mM.	Pot experiment	control: ≈1.88 g plant^{-1}; Si NPs: 1.5 mM: ≈2.44 g plant^{-1}, +30%; 3 mM: ≈2.52 g plant^{-1}, +34%; 6 mM: ≈2.80 g plant^{-1}, +49%. Si-DA6 nanocomplex: 1.5 mM: ≈2.65 g plant^{-1}, +41%; 3 mM: ≈2.99 g plant^{-1}, +59%; 6 mM: ≈3.20 g plant^{-1}, +70%. Si-Atonik nanocomplex: 1.5 mM: ≈2.52 g plant^{-1}, +34%; 3 mM: ≈2.79 g plant^{-1}, +48%; 6 mM: ≈2.97 g plant^{-1}, +58%. Sodium silicate: 1.5 mM: ≈1.94 g plant^{-1}, +3%; 3 mM: ≈1.94 g plant^{-1}, +3%; 6 mM: ≈2.30 g plant^{-1}, +22%. DA6: 1.5 mM: ≈2.42 g plant^{-1}, +29%; 3 mM: ≈2.63 g plant^{-1}, +40%; 6 mM: ≈3.04 g plant^{-1}, +62%. Atonik: 1.5 mM: ≈2.26 g plant^{-1}, +20%; 3 mM: ≈2.35 g plant^{-1}, +25%; 6 mM: ≈2.68 g plant^{-1}, +43%	Best effect: Si-DA6 6 mM: ≈3.20 g plant^{-1}, +70%.	The methodology for calculating essential oil yield is described imprecisely.	[68]
Salvia officinalis L.	TiO_2 NPs, anatase	10–15	Foliar spray; 0, 10, 50, 100, 200, 1000 mg L^{-1};	Greenhouse pot experiment	control: 0.0141 g plant^{-1}; 10 mg L^{-1} 0.0193 g plant^{-1} = +36.9%; 50 mg L^{-1} 0.0278 g plant^{-1} = +97.2%; 100 mg L^{-1} 0.0377 g plant^{-1} = +167.4%; 200 mg L^{-1} 0.0387 g plant^{-1} = +174.5%; 1000 mg L^{-1} 0.0151 g plant^{-1} = +7.1%	Best effect: 200 mg L^{-1} / Air-dried shoots	A 100-fold discrepancy was identified in the calculation of essential oil yield. The calculation used the mass of roots from which no oil had been extracted.	[57]

Table 2. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Yield	Notes/EO Basis	Limitations	Ref.
Mentha × *piperita* L.	TiO_2 NPs	21	Foliar spray; 0, 50, 100, 150, 200, 250 mg L^{-1};	Pot experiment	control: ≈0.312 mL $plant^{-1}$; 50 mg L^{-1} ≈0.350 = +12.2%; 100 mg L^{-1} ≈0.440 = +41.0%; 150 mg L^{-1} ≈0.640 = +105.1%; 200 mg L^{-1} ≈0.540 = +73.1%; 250 mg L^{-1} ≈0.490 = +57.1%	Best effect: 150 mg L^{-1}	EO yield is reported in mL $plant^{-1}$, whereas the method is described as gravimetric; the calculation and fresh- or dry-weight basis are not explicitly specified.	[56]
Ocimum tenuiflorum L.	SiO_2 NPs + TiO_2 NPs	5.2–12.1 + 10.2–15.2	Foliar spray; Si50 + Ti50, Si100 + Ti50, Si100 + Ti100, Si200 + Ti100, Si100 + Ti200, Si200 + Ti200 mg L^{-1};	Pot experiment	control: ≈0.081 mL $plant^{-1}$; Si50 + Ti50 ≈0.145 = +79.0%; Si100 + Ti50 ≈0.180 = +122.2%; Si100 + Ti100 ≈0.343 = +323.1%; Si200 + Ti100 ≈0.292 = +260.5%; Si100 + Ti200 ≈0.125 = +54.3%; Si200 + Ti200 ≈0.034 = −58.0%	The maximum combined dose of Si200 + Ti200 reduced the essential oil yield below the control values / Fresh leaves	The yield formula and units are inconsistent. The main EO experiment included combined SiO_2 NP and TiO_2 NP treatments and a water control; corresponding single-material EO treatments were not reported in the main experiment.	[58]
Pelargonium graveolens L'Hér.	Ag NPs	5–35	Foliar spraying; 0, 20, 40, 80 mg L^{-1}	Greenhouse experiment	control: 0.31 g $plant^{-1}$; 20 mg L^{-1}: 0.38 = +22.6%; 40 mg L^{-1}: 0.46 = +48.4%; 80 mg L^{-1}: 0.22 = −29.0%	Best effect: Ag NPs 40 mg L^{-1} / Air-dried aerial parts	The calculations of essential oil yield from the raw material are incompletely presented.	[59]
Dracocephalum kotschyi Boiss.	CeO_2 NPs/bulk CeO_2	10–30/NR	Foliar spraying: 0, 50, 100, 200 mg L^{-1};	Greenhouse experiment	control: ≈0.0604 g $plant^{-1}$; CeO_2 NPs 50 mg L^{-1}: ≈0.0320 = −47.0%; 100 mg L^{-1}: 0.07098 = +17.5%; 200 mg L^{-1}: ≈0.0657 = +8.8%; bulk CeO_2 50 mg L^{-1}: ≈0.0469 = −22.4%; 100 mg L^{-1}: ≈0.0517 = −14.4%; 200 mg L^{-1}: 0.07369 = +22.0%	The maximum yield of essential oil was obtained at a bulk CeO_2 concentration of 200 mg L^{-1}; for CeO_2 NPs, it was 100 mg L^{-1}. / Derived from EO content and aerial-part DW.	The oil content in the leaves was recalculated based on the dry mass of the entire shoot. The correspondence between the raw material and the mass used in the calculation is not specified.	[60]

Table 2. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Yield	Notes/EO Basis	Limitations	Ref.
Ocimum basilicum L.,	MgO NPs $MgSO_4$ Bulk	5–20	Single foliar spray; 75, 200, 300, 600 mg L^{-1};	Controlled light culture	control: 0.0148 mL $plant^{-1}$; 75 mg L^{-1}: 0.0141= −4.7%; 200 mg L^{-1}: 0.0141= −4.7%; 300 mg L^{-1}: 0.0149= +0.7%; 600 mg L^{-1}: 0.0140= −5.4%; $MgSO_4$: 0.0126= −14.9%; Bulk: 0.0057 = −61.5%	At 600 mg L^{-1}, the essential oil content in the dry mass increased, but due to the reduction in biomass, the yield per plant did not increase. Significant decrease was observed only for Bulk MgO. / Fresh-leaf; EO content expressed on DW basis.	A hexane extract, rather than hydrodistilled oil, is used. GC-FID calibration and the conversion to oil quantity are incompletely described.	[63]
Ocimum basilicum L.,	MgO NPs	4–8	Foliar spray; 0, 25, 50, 75, 100, 150, 200 mg L^{-1};	Controlled light culture	control: ≈0.00290 mL $plant^{-1}$; 25 mg L^{-1}: ≈0.00246= −15.2%; 50 mg L^{-1}: ≈0.00194= −33.1%; 75 mg L^{-1}: ≈0.00340= +17.2%; 100 mg L^{-1}: ≈0.00279= −3.8%; 150 mg L^{-1}: ≈0.00334= +15.2%; 200 mg L^{-1}: ≈0.00525 = +81.0%	A significant increase in essential oil yield is observed at 200 mg L^{-1}. The 75, 100, and 150 mg L^{-1} variants did not differ significantly from the control. / Fresh leaves; yield based on FW.	A hexane extract is used. The conversion of leaf concentration to yield per plant is incompletely described.	[79]
Dracocephalum moldavica L.	ZnO NPs; conventional zinc suspension (Kingfol Zinc)	10–30	Foliar spray; 0, 40, 80, 160, 400 mg L^{-1}	Field experiment	ZnO NPs: control: 0.82 kg ha^{-1}; 40 mg L^{-1} ≈1.90 = +132%; 80 mg L^{-1} ≈2.70 = +229%; 160 mg L^{-1} 7.43 = +806%; 400 mg L^{-1} ≈4.05 = +394%. Zn suspension: control: 0.86 kg ha^{-1}; 40 mg Zn L^{-1} ≈1.15 = +34%; 80 mg Zn L^{-1} ≈1.85 = +115%; 160 mg Zn L^{-1} 3.95 = +359%; 400 mg Zn L^{-1} 2.82 = +228%	Best effect: ZnO NPs 160 mg L^{-1}. / Derived from EO content and shade-dried aboveground biomass	Oil yield is calculated from the oil content and dry aboveground biomass.	[66]

Table 2. *Cont.*

Plant Species	NPs Chemical Composition	Size, nm	Application/Dose	Experimental Conditions	The Relative Change in Essential Oil Yield	Notes/EO Basis	Limitations	Ref.
Dracocephalum moldavica L.	ZnO NPs + CuO NPs; Zn suspension + chelated Cu	10–30 + 40	Foliar co-application; 40 + 40, 80 + 80, 160 + 160, 400 + 400 mg L^{-1}	Field experiment	control: ≈0.81 kg ha^{-1}; ZnO NPs + CuO NPs: 40 + 40 mg L^{-1}: ≈2.55 kg ha^{-1}, +214%; 80 + 80 mg L^{-1}: ≈6.20 kg ha^{-1}, +665%; 160 + 160 mg L^{-1}: ≈7.48 kg ha^{-1}, +823%; 400 + 400 mg L^{-1}: ≈1.30 kg ha^{-1}, +60%. Zn suspension + chelated Cu: 40 + 40 mg L^{-1}: ≈1.90 kg ha^{-1}, +134%; 80 + 80 mg L^{-1}: ≈2.50 kg ha^{-1}, +208%; 160 + 160 mg L^{-1}: ≈3.48 kg ha^{-1}, +329%; 400 + 400 mg L^{-1}: ≈0.50 kg ha^{-1}, −38%	The best effect: ZnO NPs 160 + CuO NPs 160 mg L^{-1}. / Derived from EO content and shade-dried aboveground biomass.	Oil yield is calculated from the oil content and dry aboveground biomass. The use of appropriate controls is described imprecisely.	[67]
Mentha × *piperita* L.	Nano-chelated fertilizer (NCF)	–	Foliar application: nano-N: 2 mL L^{-1}; nano-P, K, Fe, Zn: 1000 mg L^{-1}; nano-Mn: 500 mg L^{-1}.	Field experiment	First mowing. control: 33.4 kg ha^{-1}; CF: = 57.6 kg ha^{-1}, +72.5%; NCF: = 35.1 kg ha^{-1}, +5.1%; 50% CF + NCF: = 66.5 kg ha^{-1}, +99.1%. Second mowing. control: 26.3 kg ha^{-1}; CF 59.2 kg ha^{-1}= +125.1%; NCF 34.4 kg ha^{-1}= +30.8%; 50% CF + NCF 60.2 kg ha^{-1} = +128.9%	The data are averaged over two seasons, 2017–2018. / Derived from dry biomass and EO content	Oil yield is calculated from biomass and oil content.	[80]

The essential oil yield is influenced not only by nanoparticles based on titanium oxide and silicon; other types of nanoparticles can also have a significant impact. In *D. moldavica*, ZnO NPs applied at a nominal Zn concentration of 160 mg L^{-1} increased essential oil yield from 0.82 to 7.43 kg ha^{-1}, or by approximately 806%, whereas at a nominal Zn concentration of 400 mg L^{-1} the increase decreased to 394% [66]. CuO NPs in the same plant species provided the maximum effect at a concentration of 80 mg L^{-1} (+741%), but at a concentration of 400 mg L^{-1} they reduced the essential oil yield by 35% [81].

The combined use of ZnO NPs and CuO NPs at a concentration of 160 + 160 mg L^{-1} increased the essential oil yield by 823%, whereas at a concentration of 400 + 400 mg L^{-1} the increase was only 60% and was not statistically significant [67]. Thus, combined treatments can provide a strong effect, but an increase in the total concentration of nanoparticles can sharply reduce their effectiveness. A similar pattern was observed when using nanoparticles made of SiO_2 and TiO_2 [58].

In *P. graveolens*, the author-reported calculated essential oil yield increased following foliar application of Fe_3O_4 nanoparticles [51]. In the first cut of 2018, yield increased from 0.819 mL $plant^{-1}$ in the control to approximately 2.92 and 3.41 mL per plant at 5 and 10 mg L^{-1}, respectively, corresponding to increases of approximately 256.5% and 316.4%. Positive responses were also reported in the second cut and in the following season.

A similar dependence on dose combination was reported for *O. basilicum*. The highest reported essential oil yield was 0.03821 mL $plant^{-1}$ at Fe_2O_3 NPs 100 mg L^{-1} plus ZnO NPs 25 mg L^{-1}, compared with 0.01100 mL $plant^{-1}$ in the untreated control (+247.4%). Increasing ZnO to 50 mg L^{-1} at the same Fe_2O_3 concentration reduced the yield to 0.03173 mL $plant^{-1}$ [50].

It should be noted that in several studies, nanoparticles were compared with bulk, ionic, or chelated forms of the corresponding elements, and no advantage of the nanoform was demonstrated. In *D. kotschyi*, the maximum yield of essential oil in the experiment with CeO_2 was also obtained using the bulk form [60]. In *M.* × *piperita*, nano-Zn at a concentration of 1000 mg L^{-1} was more effective than Zn chelate, but at 1500 mg L^{-1} the difference between the two forms decreased. These effects may reflect differences in the chemical form, the availability of nutrients, dissolution, aggregation, and the actual dose received. Consequently, the advantages of nanomaterials depend on specific conditions and cannot be considered a universal property of nanoparticles.

It is known that the use of commercial multicomponent nano-fertilizers also leads to changes in essential oil yield. The Magro NanoMix preparation increased essential oil yield in *F. vulgare* by only 9.5–14.6%, whereas the PHARMAX preparation in *C. sativum* provided an increase in essential oil yield by 84.8–189.8%. The use of *M.* × *piperita* nano-chelated fertilizer without conventional fertilizer increased the essential oil yield by only 5.1% in the first cut and by 30.8% in the second cut, whereas conventional fertilizer provided, respectively, +72.5% and +125.1%. The highest increases in essential oil yield are observed when combining 50% of the recommended conventional fertilizer dose with the nano-chelated fertilizer applied at the study's stated dose [80]. Unfortunately, due to the lack of detailed physicochemical characteristics of a number of commercial products, these results cannot be unambiguously interpreted.

Thus, the analysis of essential oil yield confirms the potential ability of nanomaterials to increase the productivity of essential oil-producing plants, but it shows that this effect is generated simultaneously through changes in biomass and oil concentration. For practical application, the most significant options are those in which an increase in oil content is combined with the preservation or growth of biomass and is not accompanied by a phytotoxic effect. It is also worth paying attention to promising options for using several nanoparticles simultaneously to increase essential oil yield, as well as the combined

use of conventional fertilizers with nano-fertilizers. Practical applications may include partial replacement of traditional fertilizers and the incorporation of nanomaterials into existing fertilizer application schemes. In a two-season field study on sweet basil, applying half the recommended dose of nitrogen, phosphorus, and potassium fertilizers (NPK) in combination with date palm pollen extract and ZnO nanoparticles increased the essential oil yield per plant by 113.2% and 110.3% compared to the full NPK dose [82]. Economic aspects were also assessed in a two-season field study on caraway. The combination of humic substances, nitrogen-enriched nanocerolite, and biofertilizers provided the highest estimated profit among the studied options [83]. Such studies confirm the practical and economic efficiency of specific treatment schemes, but broader commercial benefits require confirmation under specific production conditions.

5. The Effect of Nanoparticles on Essential Oil Composition

Unlike the indicators of essential oil content and essential oil yield, the component composition of essential oil cannot be interpreted as a single indicator with a clearly positive or negative direction of change. In most studies, the content of essential oil components was expressed as a percentage of the area of chromatographic peaks. Such data are compositionally dependent: an increase in the relative proportion of one component may be the result of both an increase in its absolute content and a decrease in the content of other compounds. Therefore, in Tables 3 and S3, the results are interpreted as changes in the relative component profile unless absolute measurements were explicitly reported. Changes in relative GC–MS peak areas alone do not demonstrate an increase in the absolute amount of a component or activation of its biosynthesis. Absolute component contents or yields were distinguished only when they were directly reported in the original study. When such data were not available, the values calculated in this review were treated as estimated component yields.

Table 3. Effects of nanoparticle treatments on the relative abundance of major essential oil constituents in medicinal and aromatic plants.

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Thymus daenensis Celak.; *Thymus fedtschenkoi* Ronn.; *Thymus vulgaris* L.	Ag NPs and SiO_2 NPs; 30–100 ppm: foliar; field	*T. daenensis*: thymol 79.46 → 86.33% at Ag NPs 60 ppm (+8.6%) and → 86.07% at SiO_2 NPs 60 ppm (+8.3%). *T. fedtschenkoi*: linalool 57.31 → 78.30% at SiO_2 NPs 30 ppm (+36.6%), but → 39.41% at 100 ppm (−31.2%); 1,8-cineole 4.01 → 10.12% (+152.4%). *T. vulgaris*: thymol 54.30 → 61.85% at Ag NPs 30 ppm (+13.9%) → 61.53% at SiO_2 NPs 30 ppm (+13.3%); at 60 ppm decreased to 48.70% (−10.3%) and 44.63% (−17.8%), respectively.	The original chemotypes were largely preserved, but the same materials and doses caused changes in different directions in various *Thymus* species.	Biological samples were pooled prior to compositional analysis. Variability in component proportions across replicates is not reported.	[84]
Satureja hortensis L.	SiO_2 NPs; 0.75–2.25 mM; foliar; greenhouse	1.5 mM: carvacrol 53.50 → 57.60% (+7.7%), thymol 1.65 → 4.80% (+190.9%), γ-terpinene 25.60 → 21.20% (−17.2%). 2.25 mM: thymol (+257.6%)	All nanoparticle concentrations shifted the profile towards carvacrol and thymol as the concentration of γ-terpinene decreased. The maximum effect was observed at 1.5 mM nanoparticle concentration for carvacrol and at 2.25 mM for thymol.	Statistical comparisons of the proportions of individual components are not presented.	[85]
Zataria multiflora Boiss.	Si NPs; size ≈10–20 nm; 1.5–6 mM; foliar; sodium silicate control	Si NPs 3 mM: carvacrol 30.80 → 38.40% (+24.7%), thymol 20.60 → 29.50% (+43.2%), linalool 16.30 → 15.40% (−5.5%). Sodium silicate 3 mM: carvacrol 34.17% (+10.9%), thymol 22.10% (+7.3%)	At 3 mM, Si NPs gave higher reported relative proportions of carvacrol and thymol than sodium silicate. The linalool proportion changed little; statistical comparisons of individual components were not reported.	Statistical comparisons of the proportions of individual components are not presented. The compositional superiority of the nanoformulation is not statistically substantiated.	[68]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Thymus vulgaris L.	Chitosan NPs; size NR; 0.05–0.2%; application to the soil	CS NPs 0.1%: thymol 33.97 → 37.45% (+10.2%), γ-terpinene 15.59 → 16.63% (+6.7%), *p*-cymene 12.77 → 14.17% (+11.0%), 1,8-cineole 4.25 → 2.96% (−30.4%). CS NPs 0.2%: thymol decreases to 32.94% (−3.0%), camphor increases to 5.12% (+17.4%)	Intermediate concentration of 0.1% formed a thymol-rich profile. At 0.2%, the thymol response was reversed, and camphor/1,8-cineole accumulated.	The treatment dose and oil-extraction protocol are described inconsistently.	[86]
Mentha × *piperita* L.	TiO_2 NPs; size NR; 50–250 mg L^{-1}; foliar; pot/net-house	150 mg L^{-1}: menthol ≈34.6 → 38.0% (+9.8%), menthone ≈13.4 → 17.8% (+32.8%), menthyl acetate ≈11.7 → 13.0% (+11.1%). 250 mg L^{-1}: the changes weakened, +4.0, +16.4 and +4.3% accordingly	TiO_2 NPs were used to enrich oil with menthol, menthone, and menthyl acetate; the most pronounced effect was observed at 150 mg L^{-1}.	Only three target components are presented. The full oil profile and confirmation of component identification are incompletely disclosed.	[56]
Mentha × *piperita* L.	Chitosan-coated Fe_3O_4 NPs; size NR; 7.5 and 15 mg L^{-1}; foliar; greenhouse	7.5 mg L^{-1}: menthol 12.8 → 38.4% (+200.0%); L-menthone 23.1 → 28.5% (+23.4%); eucalyptol 8.7 → 9.1% (+4.6%); mint furanone 9.8 → 7.6% (−22.4%). 15 mg L^{-1}: menthol 12.8 → 36.7% (+186.7%); L-menthone 23.1 → 25.6% (+10.8%); eucalyptol 8.7 → 9.4% (+8.0%); mint furanone 9.8 → 6.4% (−34.7%).	Without melatonin, both doses increased the relative proportions of menthol and L-menthone, slightly increased eucalyptol, and decreased mint furanone. The highest menthol proportion was recorded at 7.5 mg L^{-1}.	Statistical significance is not described.	[87]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Salvia officinalis L.	TiO_2 NPs; 10–15 nm; 10–1000 mg L^{-1}; foliar; greenhouse	200 mg L^{-1}: 1,8-cineole 9.5 → 21.2% (+123.2%), *cis*-thujone 18.4 → 34.5% (+87.5%), camphor 18.2 → 23.8% (+30.8%). 1000 mg L^{-1}: *cis*-thujone decrease to 14.9% (−19.0%), camphor—16.6% (−8.8%), *p*-cymene—2.3% (−54.9%), at the same time, camphene increased to 12.1% (+45.8%)	At TiO_2 NPs concentrations below 200 mg L^{-1}, an enrichment of oxygenated monoterpenes was observed.	The procedure for calculating component proportions is not fully disclosed. Not all changes are statistically significant relative to the control.	[57]
Cymbopogon flexuosus (Nees ex Steud.) W.Watson	SiO_2 NPs; 50–200 mg L^{-1}; foliar; greenhouse	150 mg L^{-1}: citral 68.15 → 87.80% (+28.8%), geranial 39.85 → 54.46% (+36.7%), neral 28.30 → 33.34% (+17.8%); geraniol 6.31 → 0.60% (−90.5%), geranyl acetate 2.46 → 1.63% (−33.7%)	A pronounced enrichment with citral/geranial-rich components, accompanied by a decrease in geraniol and geranyl acetate.	Component identification is incompletely disclosed; The ethanol control is not described, and its contribution to the compositional changes is not reported.	[55]
Ocimum tenuiflorum L.	SiO_2 NPs + TiO_2 NPs; 50–200 mg L^{-1} each NPs; foliar	100 + 100 mg L^{-1}: eugenol 20.4 → 43.3% (+112.3%), *cis*-β-elemene 10.84 → 35.3% (+225.6%). 200 + 200 mg L^{-1}: eugenol ≈13.0% (−36.3%), *cis*-β-elemene ≈6.5% (−40.0%)	The intermediate total dose significantly enriched the oil with both components, whereas the maximum dose reduced their concentration below the control level.	Only selected components are presented. The analytical methods and component names are described inconsistently.	[58]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Ocimum basilicum L.	Fe-amino-acid nanocomplexes; 0.2% (*w*/*v*) of each Fe source; foliar; Fe-EDDHA control	Fe-His: methyl chavicol 89.60 → 52.94% (−40.9%), *(E)*-caryophyllene 0.73 → 9.24% (+1165.8%), (*E*)-γ-bisabolene 0.35 → 7.33% (+1994.3%), linalool 0.30 → 5.30% (+1666.7%). Fe-EDDHA: methyl chavicol 82.14% (−8.3%), *(E)*-caryophyllene 2.53% (+246.6%)	Fe-amino-acid nanocomplexes caused the most pronounced shift from a methyl-chavicol-rich profile to a sesquiterpene-rich one; chelated Fe altered the composition less significantly. The large relative effects of minor components are associated with low control values.	Large relative increases in minor components are attributable to their low initial proportions. An increase in proportion does not confirm an increase in absolute compound yield.	[62]
Ocimum basilicum L.	Iron–urea nanocomplex; 0.1 and 0.2%; foliar; greenhouse	0.1%: sesquiterpene hydrocarbons 27.54 → 42.59% (+54.6%); oxygenated sesquiterpenes 21.51 → 31.01% (+44.2%); oxygenated monoterpenes 33.01 → 23.13% (−29.9%); *n*-decane 13.40 → 0.39% (−97.1%) 0.2% sesquiterpene hydrocarbons 41.28% (+49.9%); oxygenated sesquiterpenes 33.82% (+57.2%); oxygenated monoterpenes 23.30% (−29.4%); *n*-decane 0.12% (−99.1%)	The transition from an *n*-decane/oxygenated-monoterpene-rich profile to a sesquiterpene-rich one. At 0.2%, the number of identified compounds decreased to 20, compared to 38 in the control.	Component identification and quantitative normalization are incompletely disclosed. Component proportions do not indicate absolute yield.	[88]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Ocimum basilicum L. cv. Zhigolo	MgO NPs; 6–7 nm; 25–500 mg L^{-1}; foliar; hydroponics	50 mg L^{-1}: eugenol ≈57.30 → 57.84% (+0.9%), 1,8-cineole ≈23.78 → 13.88% (−41.6%), linalool ≈9.73 → 3.08% (−68.3%). 150 mg L^{-1}: eugenol ≈41.30% (−27.9%), 1,8-cineole ≈36.96% (+55.4%), linalool ≈16.67% (+71.3%). 500 mg L^{-1}: eugenol decreased by ≈22.4%	A sharply non-monotonic restructuring: 50 mg L^{-1} had almost no effect on the eugenol content, whereas 150 mg L^{-1} produced a profile richer in 1,8-cineole/linalool. / Component percentages were calculated in this review as component content divided by total EO content × 100, using the original mg g^{-1} FW data obtained by hexane extraction and GC-FID analysis. They are calculated composition estimates.	The proportions were calculated in the review from compound concentrations in the hexane extract. Uncertainty in the calculated proportions is not reported.	[46]
Ocimum basilicum L.	nGO; thickness 0.6–1.2 nm; 100–500 mg L^{-1}; foliar; two-year field experiment	300 mg L^{-1} on manure background: linalool 53.66 → 52.45% (−2.3%), eugenol 19.93 → 21.43% (+7.5%), 1,8-cineole 9.00 → 7.45% (−17.2%). 300 mg L^{-1} on NPK background: linalool 52.40 → 53.53% (+2.2%), eugenol 23.01 → 20.91% (−9.1%), 1,8-cineole 7.98 → 9.06% (+13.5%)	nGO caused small changes that depended on the fertilizer background. The nutrient background and harvest time had a greater impact on the profile than the treatment.	Compositional changes depend on the fertilizer background, year, and harvest. Pooling these conditions limits interpretation of the nGO effect.	[89]
Pelargonium graveolens L'Hér	Ag NPs; 20–80 mg L^{-1}; foliar; greenhouse	40 mg L^{-1}: citronellol 36.40 → 31.30% (−14.0%), citronellyl formate 12.90 → 16.30% (+26.4%), iso-menthone 6.40 → 8.70% (+35.9%). 80 mg L^{-1}: citronellol increase to 39.10% (+7.4%), citronellyl formate—15.20% (+17.8%)	At a concentration of 40 mg L^{-1}, the profile shifted from citronellol to citronellyl formate and iso-menthone; at 80 mg L^{-1}, the proportion of citronellol increased. The change in the proportion of citronellol did not coincide with the change in essential oil yield.	Statistical notation for individual components is inconsistent. The significance of changes in proportions requires cautious interpretation.	[59]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Dracocephalum kotschyi Boiss.	Se NPs and sodium selenite; 50–200 mg L^{-1}; foliar; greenhouse	Se NPs 100 mg L^{-1}: geranyl acetate 12.63%—maximum value. Sodium selenite 200 mg L^{-1}: α-pinene 6.64%—maximum value	Se treatments reduced the proportion of citral type components and shifted the profile towards geranyl acetate and α-pinene.	The composition table contains ambiguous "±" entries; the type of dispersion is not specified. Not all changes in proportions are statistically significant relative to the control.	[54]
Dracocephalum moldavica L.	CS–Se NPs; ≈50 nm; 5 and 10 mg L^{-1}; foliar	CS–Se NPs 5 mg L^{-1}: *Z*-citral 11.05 → 14.96% (+35.4%), nerol 3.85 → 7.04% (+82.9%); The concentrations of geranyl acetate and geranial remained virtually unchanged. CS–Se NPs 10 mg L^{-1}: geranial 18.69 → 21.18% (+13.3%), nerol 3.85 → 5.16% (+34.0%), however, *Z*-citral decreased by 5.2%, and geraniol by 9.7%. Ionic Se increased all five main components.	At a concentration of CS–Se NPs of 5 mg L^{-1}, the profile was enriched with *Z*-citral and nerol; increasing the dose partially reversed the response. The effect of CS–Se NPs differed from the effects of ionic Se and non-nano chitosan.	The independence of the oil-analysis replicates is described ambiguously. Uncertainty in component proportions and confirmation of identification are incompletely disclosed.	[90]
Dracocephalum moldavica L.	ZnO NPs; 10–30 nm; 40–400 mg L^{-1}; Zinc suspension; foliar; field	ZnO NPs 160 mg L^{-1}: geranyl acetate 66.50 → 57.05% (−14.2%), geranial 7.42 → 12.09% (+62.9%), neral 4.95 → 8.61% (+73.9%), geraniol 4.00 → 5.65% (+41.3%). ZnO NPs 400 mg L^{-1}: geranial and neral changed by only +3.9% and +1.2%, respectively, while geraniol increased by 117.2%. Zinc suspension at 80 mg Zn L^{-1} increased geranial by 80.3% and neral by 96.4%.	ZnO NPs redistributed the profile from geranyl acetate to free oxygenated monoterpenes; the maximum enrichment of geranial/neral was observed at 160 mg L^{-1}. The nanoform did not outperform zinc suspension in terms of all components.	Independent replication of the oil analysis is limited. The zinc suspension profile at 40 mg Zn L^{-1} is reported without replicate data.	[66]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Dracocephalum moldavica L.	ZnO NPs + CuO NPs, 1:1; 40–400 mg L^{-1} each material; foliar; field	80 + 80 mg L^{-1}: geranyl acetate 66.50 → 59.31% (−10.8%), geranial 7.42 → 11.76% (+58.5%), neral 4.95 → 7.80% (+57.6%), geraniol 4.00 → 6.11% (+52.8%). 160 + 160 mg L^{-1}: geranyl acetate decreased only by 3.6%, geranial increased by 37.9%, neral—on 42.0%. 400 + 400 mg L^{-1}: geranial and neral increased on 51.1 and 54.5%	All combinations shifted the profile from geranyl acetate to geranial/neral.	A shared control with study [81] may have been used.	[67]
Tanacetum parthenium L.	Ag NPs, 20 nm; 200–600 ppm; foliar; pot experiment	200 ppm: camphor 27.37 → 37.23% (+36.0%), *trans*-chrysanthenyl acetate 22.65 → 28.25% (+24.7%), *E*-*β*-farnesene −60.5%, caryophyllene oxide −70.2%. 600 ppm: camphor 45.13% (+64.9%), *trans*-chrysanthenyl acetate 32.04% (+41.5%), *E*-*β*-farnesene −85.3%, caryophyllene oxide −79.3%, Oxygenated monoterpenes 61.78 → 83.67% (+35.4%)	Dose-dependent enrichment of oxygenated monoterpenes was accompanied by a decrease in sesquiterpenes and a narrowing of the profile: the number of identified compounds decreased from 53 to 47.	The treatment description contains an Ag/TiO_2 discrepancy. Independent analytical replicates and variability in component proportions are not reported.	[91]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Artemisia annua L. cv. Novichok	Se NPs; ≈100 nm; 30.6 mg L^{-1}; sodium selenate 73.2 mg L^{-1}; field	Se NPs: eucalyptol 12.24 → 2.30% (−81.2%), artemisia ketone 18.66 → 9.57% (−48.7%), camphor 26.77 → 6.06% (−77.4%), germacrene D 3.67 → 7.30% (+98.9%). Sodium selenate: artemisia ketone 26.38% (+41.4%), camphor 17.66% (−34.0%), germacrene D 3.16% (−13.9%)	Se NPs and ionic Se formed fundamentally different profiles. Se NPs shifted the oil towards germacrene D, whereas sodium selenate increased the relative proportion of artemisia ketone.	Averaging across two seasons obscures differences in component profiles. An increase in relative proportion does not confirm enhanced compound synthesis.	[64]
Coriandrum sativum L.	Se NPs; 20–60 mg L^{-1}; foliar; greenhouse	40 mg L^{-1}: *n*-decanal 23.90 → 28.70% (+20.1%), (2*E*)-dec-2-enal 13.20 → 15.20% (+15.2%), (2*E*)-dodec-2-enal 16.22 → 17.60% (+8.5%). 60 mg L^{-1}: *n*-decanal 29.70% (+24.3%), (2*E*)-dec-2-enal 14.80% (+12.1%), (2*E*)-dodec-2-enal 14.23% (−12.3%), *n*-nonane—7.23% (−29.3%)	Se NPs dose-dependently enriched the *n*-decanal profile; at 60 mg L^{-1}, the response to 2E-dodecanal changed from positive to negative.	Component identification and independent analytical replication are incompletely disclosed. Variability in component proportions is not reported.	[92]
Cannabis sativa L.	Si NPs; 0.5 and 1.5 mM; foliar; greenhouse	0.5 mM: β-ocimene 14.21 → 1.70% (−88.0%), caryophyllene 7.07 → 13.07% (+84.9%), α-humulene 1.93 → 3.66% (+89.6%); hydrocarbon monoterpenes 74.23 → 61.29%, hydrocarbon sesquiterpenes 17.92 → 28.48%. 1.5 mM: β-myrcene 45.50 → 54.84% (+20.5%), β-ocimene 3.02% (−78.7%)	At 0.5 mM, the profile shifted towards sesquiterpenes; at 1.5 mM, the total monoterpenes were restored, but there was a redistribution from β-ocimene to β-myrcene.	Statistical comparisons are presented only for the major components. Peak proportions were calculated without detector-response corrections.	[65]

Table 3. *Cont.*

Plant Species	Basic Data About Experiment	Main Changes in Essential Oil Composition	General Direction of Compositional Shift/Note	Limitations	Ref.
Achillea millefolium L.	MgO NPs; ≤20 nm; 100–500 mg L^{-1}; foliar; two-year field experiment	300 mg L^{-1}: α-pinene 10.85 → 11.94% (+10.0%), 1,8-cineole 12.02 → 14.01% (+16.6%), camphor 15.05 → 16.66% (+10.7%), caryophyllene oxide 8.15 → 9.26% (+13.6%), α-bisabolol 11.88 → 9.22% (−22.4%). 500 mg L^{-1}: 1,8-cineole and camphor—+3.2 and −1.7% accordingly.	The maximum restructuring was observed at a dose of 300 mg L^{-1}. A high dose weakened the effect. The concentration of α-bisabolol decreased when MgO NPs were added at all doses.	Averaging across two years obscures seasonal differences in composition. Statistical comparisons of the proportions of individual components are not presented.	[93]

Table 3 presents 23 representative experimental series selected to illustrate major dose–response patterns, species-specific responses, and shifts in essential oil composition. The selection was not based solely on effect magnitude. Full dose-resolved data for all eligible studies are provided in Supplementary Table S3. Values marked with "≈" were estimated from figures in the original publications. Relative changes were calculated against the corresponding control. Unless otherwise stated, constituent percentages represent relative chromatographic peak areas obtained by GC-FID and/or GC-MS. NPK, nitrogen, phosphorus, and potassium; NR, not reported; NPs, nanoparticles; EO, essential oil; FW, fresh weight; CS NPs, chitosan nanoparticles; CS–Se NPs, chitosan–selenium nanoparticles; nGO, graphene oxide nanomaterial; Fe-His, iron–histidine nanocomplex; Fe-EDDHA, iron chelate of ethylenediamine-*N*,*N*′-bis(2-hydroxyphenylacetic acid); GC–FID, gas chromatography with flame ionization detection; GC–MS, gas chromatography–mass spectrometry; ppm, parts per million. In Ref. [66], zinc suspension refers to the conventional fertilizer Kingfol Zinc (Omex Agrifluid Limited, King's Lynn, UK), abbreviated as ZnS in the original study. In Ref. [66], treatment concentrations are expressed as nominal Zn concentrations. The most general pattern of the effect of nanoparticles on the composition of essential oil is not a unidirectional accumulation of all main components, but a redistribution of their relative proportions. In *S. hortensis* plants, SiO_2 NPs increased the relative proportions of carvacrol and thymol, while simultaneously reducing the proportion of γ-terpinene [85]. In *C. flexuosus*, treatment with 150 mg L^{-1} SiO_2 NPs increased the relative proportion of citral from 68.15 to 87.80%, while geraniol decreased from 6.31 to 0.60%, and geranyl acetate decreased from 2.46 to 1.63% [55]. In experiments with *D. moldavica*, ZnO NPs, CuO NPs, and hybrid ZnO/CuO NPs altered the quantitative ratio of compounds such as geranyl acetate, geranial, neral, and geraniol. These results may be explained by the redistribution of metabolites between interconnected branches of biosynthesis; however, it should be remembered that changes in the relative proportions of individual secondary metabolites do not prove the activation of specific enzymes or metabolic pathways.

Nanoparticles of different chemical nature often produce similar increases in the relative proportions of some secondary metabolites. Thus, in thymol- and carvacrol-rich members of the Lamiaceae family, spraying with nanoparticles often shifts the relative oil profile toward phenolic monoterpenes. In *Zataria multiflora* Boiss. plants, pure Si NPs increased carvacrol from 30.80 to 38.40% and thymol from 20.60 to 29.50% at 3 mM [68]. For *T. vulgaris* Ag NPs at 50–100 mg L^{-1}, the proportion of thymol increased from 30.94 to 40.69–42.08%, while simultaneously reducing γ-terpinene and 1,8-cineole [94]. In studies on *M.* × *piperita* plants, TiO_2 NPs predominantly shifted the oil composition towards menthol and menthone. At 150 mg L^{-1}, their proportions increased from approximately 34.6 to 38.0% and from 13.4 to 17.8%, respectively [56]. In another experiment, 100 mg L^{-1} TiO_2 NPs increased menthol from 29.8 to 34.4% and menthone from 24.6 to 28.8%, but simultaneously reduced 1,8-cineole from 16.89 to 12.55% and increased menthofuran from 2.1 to 3.1% [95]. Nano-Zn also increased the relative proportions of menthol and menthone, but this was accompanied by an increase in the relative proportion of menthofuran and a decrease in β-caryophyllene and linalool [96]. Fe_2O_3 NPs increased menthone, and the combination of Fe_2O_3 NPs with high salinity sharply disrupted the original mint chemotype [69].

At the same time, it is important to note that the literature describes cases where closely related species react to the same nanoparticle preparation in different ways. For example, in one field study, Ag NPs and SiO_2 NPs at a concentration of 60 ppm increased the thymol concentration in *Thymus daenensis* Celak. from 79.46 to 86.33 and 86.07%, respectively, but reduced the concentration of this secondary metabolite in *T. vulgaris* from 54.30 to 48.70 and 44.63% [84]. In *Thymus fedtschenkoi* Ronniger plants, low doses of SiO_2 NPs increased the linalool content [84], whereas in the same species, SiO_2 NPs at 100 ppm reduced the

linalool proportion from 57.31 to 39.41% and increased 1,8-cineole and borneol. Therefore, belonging to the same genus or family does not guarantee a uniform response to the same nanoparticle preparation.

An analysis of the articles allows us to assert that the relationship between changes in the relative proportions of essential oil components and the concentration of nanoparticles is often not linear. For example, in the *S. officinalis* plant, an increase in the concentration of TiO_2 NPs from 10 to 200 mg L^{-1} was accompanied by a consistent increase in 1,8-cineole from 9.5 to 21.2% and *cis*-thujone from 18.4 to 34.5%. At 1000 mg L^{-1}, the content of *cis*-thujone decreased to 14.9%, camphor to 16.6%, and *p*-cymene to 2.3% [57]. When SiO_2 and TiO_2 NPs were used together in *C. aromaticus* and *O. tenuiflorum* plants, the most pronounced enrichment with target components was observed up to a concentration of 100 + 100 mg L^{-1}, whereas a concentration of 200 + 200 mg L^{-1} led to a decrease in the proportion of these compounds below the control values [58,71]. In *M. chamomilla* L. plants, at ZnO NP concentrations up to 80 mg L^{-1}, an increase in the relative proportion of α-bisabolol oxide A was observed, whereas at 160 mg L^{-1}, a sharp decrease and enrichment of the essential oil with α-bisabolol oxide B was observed.

Changes in the relative proportions of different classes of volatile compounds under the influence of nanoparticles of varying chemical nature are not universal. In *T. parthenium* plants, Ag NPs dose-dependently increased the proportion of oxygenated monoterpenes from 61.8 to 83.7%, mainly due to increases in the relative proportions of camphor and *trans*-chrysanthenyl acetate. On the contrary, in *Artemisia annua* L., Se NPs decreased eucalyptol, artemisia ketone, and camphor, but increased germacrene D [64]. In *Cannabis sativa* L., 0.5 mM Si NPs decreased hydrocarbon monoterpenes from 74.23 to 61.29% and increased hydrocarbon sesquiterpenes from 17.92 to 28.48%, whereas at 1.5 mM the total proportion of monoterpenes returned to the control level, but the internal profile shifted from β-ocimene to β-myrcene.

A comparison of the strength of the effect exerted on the plant by nanoparticles compared to ionic and bulk materials did not confirm the universal advantage of the nanoform. Nano- and bulk-CeO_2 caused a similar reduction in geranial and neral and an enrichment in 3-carene and geranyl acetate in *D. kotschyi*, and for some components, the bulk material had a more pronounced effect [60]. In *Mentha* × *gracilis*, conventional Ti altered the composition more significantly than TiO_2 NPs, sharply reducing linalool and increasing *trans*-caryophyllene, germacrene D, and *n*-decane [97]. Se NPs and sodium selenate in *Artemisia annua* formed fundamentally different profiles [64]. Based on general considerations, nanoparticles may not be more effective compared to true solutions of the same chemical composition, while the effect of nanoparticles should be more prolonged. We have not found any direct evidence to support this assumption in the literature, which is why the study of the prolonged effect of nanoparticles on the component composition of essential oils in plants may have a notable level of novelty.

In most published original studies, the absolute yield of individual components of the essential oil is not provided. Instead, the relative proportion of the components in the oil is indicated, usually based on the peak areas obtained using gas chromatography–mass spectrometry. Therefore, in cases where the necessary data were available, the yield of an individual component was calculated based on the total yield of the essential oil and its relative proportion.

For practical assessment, it is necessary to jointly analyze the proportion of a specific secondary metabolite and the total yield of essential oil. The estimated yield of a specific secondary metabolite can be expressed as.

$$Y_i = Y_{EO} \times \frac{p_i}{100}, \quad (2)$$

where Y_i is the estimated yield of a specific secondary metabolite. Y_{EO} is the total essential oil yield. p_i is the relative constituent abundance (%). When p_i is derived from relative chromatographic peak area, Y_i represents an approximate yield.

Equation (3) expresses the relative change in estimated component yield between a treatment and its corresponding control (for example, when comparing a new plant treatment method with the conventional one):

$$\Delta Y_{i(\%)} = \left[\left(1 + \frac{\Delta Y_{EO}}{100}\right)\left(\frac{p_{p,T}}{p_{p,C}}\right) - 1\right] \times 100, \quad (3)$$

where $\Delta Y_{i(\%)}$ is the required relative change in the yield of the *i*-th secondary metabolite (in percent). ΔY_{EO}—change in the total essential oil yield (in percent). $p_{p,T}$—the proportion of the secondary metabolite in the experimental/test sample. $p_{p,C}$—the proportion of the secondary metabolite in the control sample.

For example, in *P. graveolens* Ag NPs at a concentration of 40 mg L^{-1}, the proportion of citronellol decreased from 36.4 to 31.3% (−14.0% relative to the control), but the yield of essential oil increased by 48.4%. The calculation we performed shows that the estimated yield of citronellol could have increased by approximately 27.6%. At a concentration of 80 mg L^{-1}, the proportion of citronellol, on the contrary, increased to 39.1%, but the total yield of essential oil decreased by 29%. The estimated citronellol yield calculated using Equation (3) decreased by approximately 23.7%. These estimates were obtained by combining compatible data from Tables 2 and 3. They were not directly reported as absolute component yields in the primary publications and should not be interpreted as confirmed absolute quantitative measurements.

A similar difference is observed for *S. officinalis* plants. At a TiO_2 NP concentration of 200 mg L^{-1}, the total oil yield increased by 174.5%, and the proportion of *cis*-thujone increased from 18.4 to 34.5%; the estimated yield of *cis*-thujone increased by approximately 414.7%. At a concentration of 1000 mg L^{-1}, the total oil yield was 7.1% higher than the control, but the proportion of *cis*-thujone decreased to 14.9%, as a result of which the estimated yield of *cis*-thujone decreased by approximately 13.3%. Thus, an increase in total essential oil yield may be accompanied by a decrease in estimated component yield, whereas a decrease in relative component abundance may coincide with an increase in estimated component yield.

Thus, the use of nanoparticles often led to coordinated changes in the relative proportions of metabolically linked components, and changes in the opposite direction in the content of antagonistic elements. In thymol- and carvacrol-containing essential oils, an increase in the relative proportions of these phenolic monoterpenes was often accompanied by a decrease in the proportion of γ-terpinene; in mint, the profile shifted towards menthol and menthone with a reduction in the content of 1,8-cineole and linalool; in basil, Fe-containing nanocomplexes reduced the proportion of methyl chavicol and increased the relative proportions of caryophyllene, germacrene D, and bisabolene. For practical agriculture, the following conclusion can be drawn: nanoparticles can be used to selectively enrich oil with specific groups of compounds and to form the required component profile.

6. Discussion

The set of publications reviewed shows that nanomaterials can increase the content and overall yield of essential oil, as well as alter its component composition. The effect of nanoparticles is better viewed as regulatory. Treating a plant with nanoparticles changes the balance between the processes responsible for plant growth and essential oil accumulation, as well as the efficiency of the synthesis processes of various secondary metabolites. However, changes in the relative composition of the oil alone do not establish changes

in biosynthetic rates. The direction and intensity of these processes depend on the effective concentration achieved in the tissues, and the range of the stimulating effect is often relatively narrow.

In Figure 2, essential oil yield increased numerically in 177 of 190 treatment–control comparisons (93.2%) and decreased in 13 (6.8%); none had an exactly zero numerical change. These percentages refer to yield only. This descriptive percentage does not indicate the proportion of statistically significant or independently reproducible effects, and multiple comparisons from the same publication do not constitute independent evidence. The predominance of numerical increases may partly reflect selective reporting within studies and preferential publication of positive findings. The median of publication-specific medians was +54.0% for TiO_2 NPs (10 publications), +48.5% for Si/SiO_2 NPs (7 publications), +66.5% for Fe/iron oxide NPs (6 publications), and +51.1% for Zn/ZnO NPs (11 publications). The largest group median was +230.8% for Cu/CuO NPs, but it was based on only two publications. All group medians were positive, although individual comparisons included decreases. These unweighted summaries do not establish superiority of one nanomaterial over another.

Tables S1 and S2 include multiple examples in which increasing the nanoparticle concentration did not consistently increase essential oil content or yield. Figure 2 summarizes treatment–control changes and does not itself quantify the frequency or shape of dose–response relationships. In sage and peppermint, the maximum response to TiO_2 NPs was achieved at an intermediate concentration investigated in the experiment, after which the stimulating effect diminished [56,57]. A similar pattern was observed when SiO_2 NPs were used in lemongrass [55], ZnO [66] and CuO NPs [81] in Moldavian bugloss, and with combinations of SiO_2 NPs and TiO_2 NPs in coleus and fine-flowered basil [58,71]. These results are consistent with a hormetic type of response, but they do not in themselves establish its mechanism. The reduction in the strength of the effect at high concentrations of nanoparticles may be due not only to increased oxidative stress but also to disruption of the mineral balance, the toxicity of released ions, particle aggregation, and saturation of absorption pathways. Overall, a detailed study of these mechanisms could be a topic for future research.

The difference between the oil content in the plant material and its total yield is of great importance. These indicators did not coincide in direction in all studies. For example, in *Dracocephalum kotschyi* Boiss., Se NPs at high concentrations reduced the oil content but increased its yield due to an increase in biomass [54]. The opposite situation was observed in *Pelargonium graveolens*: Ag NPs increased the oil content in plant tissue but reduced its yield from the plant [59]; a similar effect was found for CeO_2 NPs in *D. kotschyi* and MgO NPs in basil [60,63].

Nanomaterials redistributed the relative proportions of metabolically linked components. In thymol- and carvacrol-containing oils, an increase in the proportion of these phenolic monoterpenes was often accompanied by a decrease in the content of γ-terpinene [85,94]. In the case of *Moldovan snakehead*, the ratio of geranyl acetate, geranial, neral, and geraniol was altered by ZnO- and CuO NPs [66,67,81], while in lemongrass, the accumulation of citral was accompanied by a decrease in geraniol and geranyl acetate [55]. In basil, Fe-containing nanocomplexes reduced the proportion of methyl chavicol and shifted the profile towards caryophyllene, germacrene D, and other sesquiterpenes [62,88]. Therefore, a more likely result of treating plants with nanoparticles is a change in the distribution of metabolic flux between the branches of terpene and phenylpropanoid metabolism, rather than a proportional increase in all oil components.

An increase in the relative proportion of menthol, thymol, carvacrol, citral, or khusimol may be technologically desirable; however, in some experiments, the content of menthofuran,

pulegone, thujone, camphor, estragole, or methyl eugenol also increased simultaneously. Furthermore, the biological properties of the oil may depend on the interaction of the main and minor compounds. Therefore, quality cannot be assessed by an increase in a single dominant component: it must be determined by the product's purpose, compliance with the required profile, and the absolute content of both target and undesirable substances [13]. It is likely that one of the scientific and industrial challenges of the future will be to develop treatment schemes for plants that will increase the relative proportions of desired secondary metabolites or their absolute amounts when directly measured while inhibiting the synthesis of undesirable secondary metabolites.

Nanoparticles of different chemical nature often produce similar changes in the relative proportions of the same secondary metabolites. At the same time, the literature describes cases where closely related species respond to the same nanoparticle preparation in different ways. The most striking illustration of this idea is the results obtained on various species of the thyme plant. Ag NPs and SiO_2 NPs increased the proportion of thymol in *Thymus daenensis*, but at the same concentration they reduced it in *T. vulgaris* [84]. In *T. fedtschenkoi*, SiO_2 NPs at 30 ppm increased the relative proportion of linalool, whereas at 100 ppm they decreased linalool and increased the relative proportions of 1,8-cineole and borneol [84]. It is known that the biosynthesis of thymol and carvacrol involves the sequential participation of specialized terpene synthases, monooxygenases of cytochrome P450 subfamily 71D (CYP71D), and short-chain dehydrogenases/reductases [98]. Therefore, opposite changes in the profile can occur when a nanomaterial acts on different stages of a single metabolic sequence. For the same reason, changes in the percentage content of a specific secondary metabolite must be interpreted in conjunction with the total oil yield. In the plant *P. graveolens*, Ag NPs at one concentration reduced the relative proportion of citronellol, but due to an increase in the total oil yield, its calculated amount increased [59]. At a higher concentration of Ag NPs, the proportion of citronellol increased, but its estimated yield decreased along with the total essential oil yield [59]. A similar relationship has been identified in sage for *cis*-thujone. Consequently, an increase in the proportion of the target component does not necessarily increase the amount of the resulting substance, and a decrease in its proportion does not always mean a reduction in productivity. In further studies, the main indicator should be the absolute yield of the component per plant or per unit area, determined using an internal standard.

A comparison of nanoparticles with soluble, chelated, and bulk forms did not reveal a universal advantage of nanomaterials. In some studies, Se NPs, Fe_2O_3 NPs, and MgO NPs outperformed the corresponding comparative forms, while in others, a pronounced effect was provided by bulk CeO_2 or conventional fertilizer. This means that the observed response cannot be automatically attributed to the particle size. It may be determined by the availability of the element, the composition of the coating or ligand, and differences in the actually delivered dose. Overall, this issue requires further study. Nanoparticles usually dissolve in water rather slowly, which means that the contents of the nanoparticle do not immediately enter the surrounding liquid; instead, they do so gradually. It can be assumed that the effect of nanoparticles on plants should be more prolonged compared to true solutions of the same chemical composition. In this regard, studying the prolonged effect of nanoparticles on the component composition of essential oils in plants may be promising.

It is also necessary to consider the additive effect observed when using combinations of nanoparticles. Today, it is known that the combined use of ZnO NPs + CuO NPs [67] or SiO_2 NPs + TiO_2 NPs [58] has an additive effect on the content and yield of essential oil. Investigating the mechanisms underlying this phenomenon can serve as the focus of future research.

Previously, an increase in the essential oil productivity of peppermint after treatment with TiO_2 NPs was demonstrated. The increase in essential oil productivity was accompanied by an increase in photosynthetic efficiency, as well as in the density and diameter of peltate glandular trichomes [56]. In vetiver, exposure to nanomaterials simultaneously increased photosynthetic parameters and oil yield and changed the reported relative proportion of khusimol [34], while the combined use of SiO_2 NPs and TiO_2 NPs in *O. tenuiflorum* altered photosynthetic efficiency, the morphology of secretory structures, essential oil content, and eugenol concentration [58]. A distinctive feature of these studies is the increase in essential oil content and yield against the backdrop of increased photosynthetic efficiency and the development of glandular trichomes. The essence of this relationship and the possible molecular mechanisms remain to be elucidated in the future.

Direct evidence of the mechanisms exists only for a small number of nanoparticles. In peppermint, TiO_2 nanoparticles altered the content of hydrogen peroxide and malondialdehyde, the activity of antioxidant enzymes, and the expression of genes encoding geranyl diphosphate synthase (GPPS), menthone reductase (MR), and menthofuran synthase (MS), which are involved in menthol-related monoterpene metabolism [33]. In lemongrass, silicon nanoparticles were studied together with photosynthetic gas exchange, chlorophyll fluorescence, the content of hydrogen peroxide and substances that react with thiobarbituric acid, the activity of antioxidant enzymes, and the activity of geraniol dehydrogenase [55,99]. Other studies directly measured hydrogen peroxide, superoxide, malondialdehyde, or the activity of antioxidant enzymes in *Mentha arvensis* L. [100]. Direct measurements of photosynthesis parameters and the characteristics of glandular trichomes were recorded for peppermint [56,101], *O. tenuiflorum* [58], and *C. aromaticus* [71]. These studies demonstrate the relationship between nanoparticle treatment, redox status, photosynthetic activity, glandular trichomes, and the properties of essential oils. However, the established facts do not allow us to establish a single cause-and-effect mechanism applicable to all combinations of plants and nanoparticles.

Accordingly, Figure 3 is presented more as a conceptual framework. The first level, associated with photosynthesis, biomass, and, in some studies, parameters related to mineral nutrition, is primarily confirmed by direct physiological measurements. The second level, associated with glandular trichomes, is confirmed by a limited number of morphological studies using microscopy. The third level, associated with the redistribution between biosynthetic pathways, remains more hypothetical, since most studies report relative areas of chromatographic peaks rather than direct measurements of metabolic flux or absolute metabolite production. Direct evidence of molecular or enzymatic changes is currently limited to individual measurements of GPPS, MR, and MS gene expression [33] and geraniol dehydrogenase activity [55,99].

The synthesis of results is hampered not only by the relatively small number of experimental publications but also by methodological shortcomings in many of them. The most common problems include incomplete characterization of nanomaterials, the absence of comparable ionic and bulk controls, insufficient detail on dosing, and inconsistencies in calculations of essential oil content and yield. Analyses of oil composition also often omit information needed to confirm compound identification and estimate relative proportions.

Future studies should therefore characterize the particles and working suspensions more clearly, describe treatment methods and actual applied doses in detail, use appropriate positive and negative controls for comparison, include independent biological replicates, and provide a transparent account of statistical analyses. Oil content and yield should be determined using the same plant material, with fresh or dry mass specified. Changes in composition should be supported by reliable compound identification and, where possible, by measurements of the absolute amounts of target constituents. Repeating such experi-

ments across different crops and growing conditions will help establish which effects are reproducible and of practical significance.

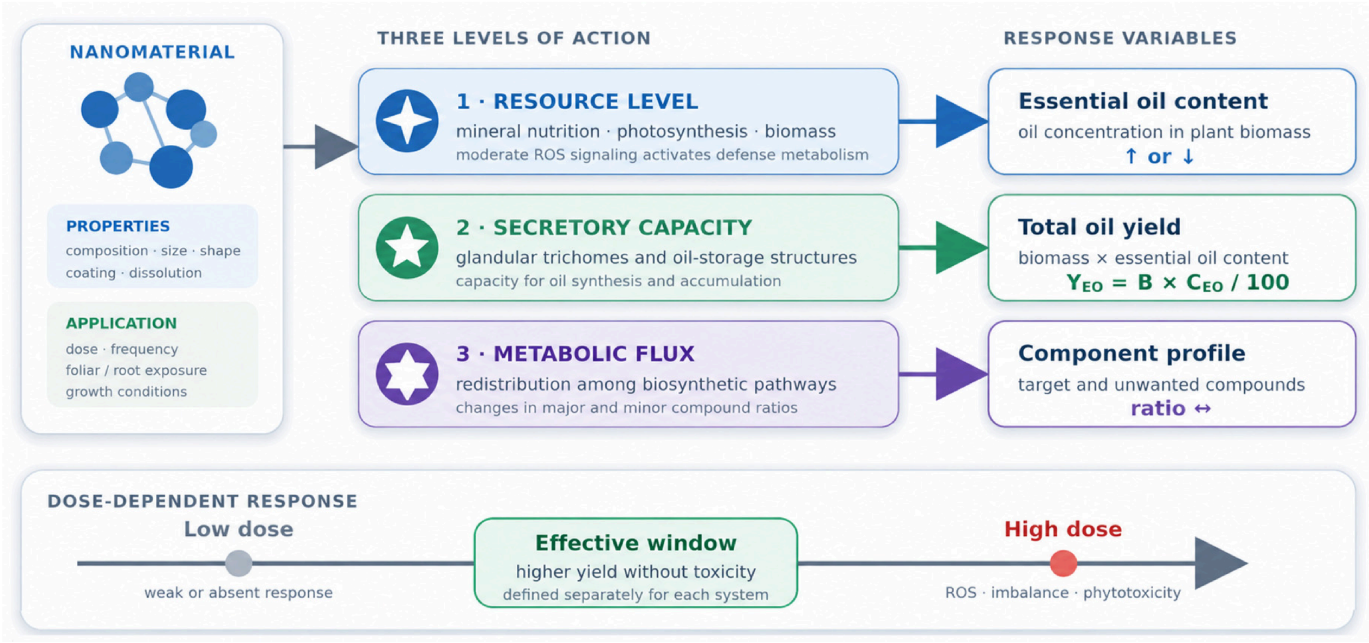

Figure 3. Conceptual framework illustrating possible levels through which nanomaterials may affect essential oil production. The depicted levels and arrows do not imply a universally established causal sequence.

7. Limitations

It is clear that nanomaterials can affect the quantitative and qualitative composition of essential oils. However, the available data are currently insufficient to reliably predict the effect of a specific treatment. The tabulated evidence comprises 85 unique experimental publications, but a significant portion of the data consists of concentration series from individual experiments, and direct independent replication of identical experiments was extremely rare. Experiments with plants of the Lamiaceae family account for 138 of the 193 rows in Tables S1–S3 (71.5%); foliar treatments and analysis of above-ground organs predominate. Overall, the evidence supporting the effectiveness of individual nanomaterials at the concentrations used is often lacking independent confirmation, and knowledge about the proposed mechanisms remains limited.

The comparability of the data obtained in the studies under analysis was further reduced by differences in the plant development stage, the parts and organs of the plants analyzed, the use of fresh or dry mass, the duration of treatment, growing conditions, and methods of oil extraction. The yield of essential oil is expressed in various units in the literature. Essential oil content was reported on different fresh- or dry-weight bases, whereas total essential oil yield was reported per plant, plot, or unit of cultivated area (most often per hectare). When analyzing the component composition of essential oil, only the relative areas of the selected chromatographic peaks are often provided, and statistical significance is often not reported. Articles do not always provide the necessary information about nanoparticles. Often, the average size, particle size distribution, ζ-potential, coating, crystalline phase, information about the tendency to aggregate, and the dissolution rate in the working medium are not provided. As a result, the same nominal concentration may correspond to different deposited and absorbed doses.

The methodology used to search for literature for the review also has its limitations. The search was conducted primarily using English-language terms, so works indexed only in

other languages might have been missed. Due to the heterogeneity of the indicators, a meta-analysis was not conducted, and patterns were identified through qualitative comparison. Some values were determined from graphs, and a formalized assessment of the risk of systematic error in the primary studies was not performed.

Taken together, these limitations reduce the comparability of the available data and the ability to generalize the obtained results. It cannot be assumed that the positive effect observed in one species of the Lamiaceae family, when applied foliarly or at a certain nominal concentration of nanoparticles, will be maintained in another plant species, in a different growing system, with a different application method, or with a different form of nanomaterial. Therefore, the available data are more suitable for identifying patterns characteristic of specific systems and formulating testable hypotheses than for developing general recommendations.

Environmental consequences and safety issues require a separate assessment. Nanoparticles or released ions may remain on the surface of plants, enter the soil or rhizosphere through runoff and with plant residues, or accumulate in the biomass of medicinal plants. Their behavior and subsequent fate in the environment depend on the composition of the particles, coating, size, aggregation, dissolution, application rate, and method of application. Some studies have demonstrated the transfer of nanoparticles from leaves to the rhizosphere [31], but the significance of this process for essential oil crops remains uncertain. The studies included in this review primarily assessed short-term plant responses and rarely provided data on the residual content of nanoparticles, their environmental stability, their effect on soil microorganisms or non-target organisms, the impact of repeated application over several seasons, or their safety for consumers.

8. Conclusions

Overall, nanomaterials have significant potential for targeted regulation of essential oil productivity, but the outcome is determined by a combination of factors: on the one hand, the species, chemotype, and growing conditions of the plant, and on the other hand, the chemical structure, concentration, and method of delivery of the nanoparticles. The maximum effectiveness of using nanoparticles is observed within a narrow range of effective concentrations; beyond this range, the stimulating effect of nanoparticles weakens or gives way to phytotoxicity. The absence of a universal advantage of the nanoform over ionic and bulk analogues shows that practical value must be demonstrated for each system separately. It is not possible to limit oneself to the maximum percentage content of essential oil or an increase in the share of a single dominant component. A promising technology must simultaneously increase or preserve biomass and enhance the essential oil yield, as well as maintain the required chemotype and absolute yield of target compounds, while reducing the relative proportions or, where directly measured, the absolute amounts of undesirable components and without creating unacceptable residual/environmental risks. In practical terms, the results obtained can serve as the basis for technologies aimed at increasing the essential oil yield and deliberately shaping their component profile for the food, pharmaceutical, and perfumery and cosmetics industries, as well as for the production of plant protection products.

To improve comparability, future studies should adopt a standardized minimum experimental and reporting framework, specifying plant identity and chemotype, growing and harvesting conditions, nanoparticle characteristics, delivered doses, appropriate controls, and independent biological replicates. Essential oil content, yield, and composition should be measured using clearly documented methods, with the fresh- or dry-weight basis and units explicitly stated. Combined treatments should include single-component controls, and changes in biological activity should be tested directly when functional benefits are claimed.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/plants15233740/s1: Excel containing three worksheets: Table S1: Effects of nanoparticle treatments on essential oil content in medicinal and aromatic plants; Table S2: Effects of nanoparticle treatments on essential oil yield in medicinal and aromatic plants; Table S3: Effects of nanoparticle treatments on essential oil composition in medicinal and aromatic plants. References [102–133] are cited in the Supplementary Materials.

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Abbreviations

Arg	Arginine
CF	Chemical fertilizer
CS NPs	Chitosan nanoparticles
CS–Se NPs	Chitosan–selenium nanoparticles
CYP71D	Cytochrome P450 subfamily 71D
DA6	Diethyl aminoethyl hexanoate
DAP	Days after planting
DOXP	1-Deoxy-D-xylulose 5-phosphate
DW	Dry weight
EO	Essential oil
Fe-EDDHA	Iron chelate of ethylenediamine-*N*,*N*′-bis(2-hydroxyphenylacetic acid)
Fe-His	Iron–histidine nanocomplex
FW	Fresh weight
GC–MS	Gas chromatography–mass spectrometry
GPPS	Geranyl diphosphate synthase
Gly	Glycine
GO NPs	Graphene oxide nanoparticles
His	Histidine
MEP	2-C-Methyl-D-erythritol 4-phosphate
MR	Menthone reductase
MS	Menthofuran synthase
NCF	Nano-chelated fertilizer
nGO	Nano graphene oxide
NPK	Nitrogen, phosphorus, and potassium
NPs	Nanoparticles
NS	Nanoscale silver
NR	Not reported
nSi	Nanosilicon

ROS	Reactive oxygen species
SEM	Scanning electron microscopy
SSe	Sodium selenite
TEM	Transmission electron microscopy
IQR	Interquartile range
ppm	Parts per million
v/*w*	Volume/weight
w/*w*	Weight/weight
w/*v*	Weight/volume

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