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Review

Biological Activities of *Zingiber officinale* Roscoe Essential Oil against *Fusarium* spp.: A Minireview of a Promising Tool for Biocontrol

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Abstract: *Zingiber officinale* Roscoe is an herbal plant native to Asia that can be found in all tropical countries. It is used in folk medicine, food, and cosmetics. A chemical characterization and some agronomic experiments have been carried out on *Z. officinale* essential oil, showing promising findings for the biological control of fungal pathogens belonging to the genus *Fusarium*. The aim of this review is to collect and update the literature covering its phytochemistry and biological activities as a *Fusarium* spp. plant-based biocide. The present research was conducted using the following bibliographic databases: Scifinder, Pubmed, and Science Direct. Thirteen papers were selected based on the adopted criteria. Data were independently extracted by the three authors of this work, and the final article selections were completed in a manner that avoided the duplication of data. The main chemical compounds were α-zingiberene, geranial, and aryl-curcumene, but a remarkable difference was found concerning the chemical compositions. *Z. officinale* essential oil was shown to possess promising biological functions against *Fusarium* spp. These findings offer new research approaches and potential applications as a biocontrol ingredient for *Z. officinale* essential oil.

Keywords: phytopathogens; essential oils; post-harvest control

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1. Introduction

Several fungal species belonging to the *Fusarium* genus are phytopathogens and cause severe yield and quality losses for cultivated cereal grains such as maize, wheat, and rice [1] as well as plants such as coriander, cumin, fennel, and fenugreek [2]. *Fusarium* members can also be found as contaminants in stored agricultural commodities. Globally, there are grave concerns related to economic losses due to decreases in field production and contamination with mycotoxins [1].

The most common phytopathogen species are *F. oxysporum* [3], *F. graminearum* [1,4], *F. verticillioides* [5], and *F. moniliforme*. *Fusarium* spores are usually found in soil, and they infect plants through their roots. *Fusarium* species are causative agents of vascular system diseases that lead to the deterioration of host soft tissues and, consequently, plant necrosis [1,3]. Concerns also include the contamination of agricultural commodities with mycotoxins, which are secondary toxic metabolites produced by some fungal species, especially those belonging to the *Aspergillus*, *Penicillium*, and *Fusarium* genera.

The Food and Agriculture Organization estimates that about 25% of the world's food crops are contaminated with mycotoxins; this has been recognized as a major health and economic problem due to the acute and chronic diseases they cause in humans and animals. Mycotoxin ingestion may lead to several health problems, such as carcinogenesis, neurotoxicity, and immunosuppressive effects; their toxicity may vary according to fungal species, human age, nutrition, and length of exposure. Hundreds of mycotoxins have been characterized, but the most relevant in terms of toxicity and occurrence are aflatoxins (AFs), ochratoxins (OTs), fumonisins (FMs), and trichothecenes (TRCs) [6].

The conventional treatment of infectious plant diseases caused by *Fusarium* involves the use of synthetic fungicides, but the adverse effects on the environment and human health require the development of safer solutions. Essential oils (EOs) have received attention from the research community due to their potential for developing biodegradable and plant-based fungicides [7,8].

EOs have been extensively investigated in many research fields, including pharmacology, food flavoring, soaps, cosmetics, and natural insecticides [9–12]. A large number of applications have been developed, and the scientific interest in EOs has increased in the last few decades. With respect to food science, the efficacy of EOs as antioxidant and antimicrobial food additives has been reported by several authors [13,14], and some interesting findings have been reported regarding the reduction in lipid oxidation in extra-virgin olive oil (EVOO) [15], antimicrobial and antioxidant activity in meat [16], the extension of shelf-life in vacuum-packaged fish fillets [17], and the preservation of unpasteurized fruit juice [18]. Additionally, EOs have been studied as additives for nanoemulsions [19] and edible films for food preservation [20]. All of these findings encourage new research concerning the use of EOs in food science.

EOs are oily liquids with a typical aromatic fragrance that are derived from a large number of plants; they can be obtained from different anatomical parts, such as leaves, flowers, bark, seeds, twigs, fruits, and roots. As reported by Sadgrove and Jones (2015), at the beginning of the 16th century, the concept of Eos was conceived by a Swiss medical pioneer who was studying a drug called "*Quinta essentia*" [21]. Essential oils have been identified as complex mixtures of several volatile compounds, including monoterpenes, sesquiterpenes, esters, ketones, aldehydes, and alcohols. A complete definition of EOs must include the extraction method because only steam distillation, dry distillation, and mechanical extraction from the epicarp of citrus fruits are acceptable methods that distinguish an EO from similar vegetal extracts, such as absolutes, concretes, alcoholates, and oleoresins [22].

Zingiber officinale Roscoe is a perennial herb belonging to the Zingiberaceae family and native to Southeast Asia and the Pacific Islands (Figure 1). Rhizomes are very popular in Asian folk medicine, and their traditional uses are widespread all over the world, mainly as flavoring agents for foods and beverages and as herbal remedies. Several authors have summarized the chemical composition of these plants [23,24], and some modern research articles have revealed new findings concerning their potential to ameliorate memory dysfunctions [25], metabolic syndromes [26], obesity management [27], and vascular diseases [28].

Figure 1. Root of *Zingiber officinale* Roscoe.

Additionally, the antimicrobial activities of *Z. officinale* derivatives have been investigated [29,30]; however, a specific focus on their potential as bio-microbicides is needed. The present study aimed to investigate the antifungal effect of *Z. officinale* EO against *Fusarium* spp. in order to describe the "state of the art" of a potential new plant-based treatment. The results may be useful for identifying novel strategies for the control of fungal pathogens belonging to the genus *Fusarium*.

2. Materials and Methods

Based on the PRISMA guidelines [31], the present review article was developed by selecting articles from the following scientific databases: PubMed (https://pubmed.ncbi.nlm.nih.gov/, accessed on 8 December 2021), SciELO (https://scielo.org/, accessed on 8 December 2021), ScienceDirect (https://www.sciencedirect.com/, accessed on 3 December 2021), SciFinder (https://scifinder.cas.org, accessed on 7 December 2021), and Wiley (https://onlinelibrary.wiley.com/, accessed on 6 December 2021). Mendeley software (https://www.mendeley.com/, accessed on 6 December 2021) was used to manage all bibliography references, and the search for and selection of the articles were independently performed by three researchers (i.e., LS, NRM, and MR) in a manner that avoided the duplication of data. The following keywords were used: "*Zingiber officinale* essential oil" and "*Fusarium*". Both keywords were searched individually and in combination. Although we considered the literature of the past 20 years, we also included some key data in the Introduction and Discussion sections. Tables were prepared to represent the following criteria: the country where the research was performed, the main compounds found in the oil, the assay, the pathogen species, the results concerning antimicrobial activity, and the positive and negative controls. As reported in Figure 2, the above-mentioned criteria allowed the selection of 13 eligible articles, excluding 45 articles that did not meet the selection methodology either due to incomplete information or because they simply mentioned data concerning *Fusarium* infection without focusing on the topic of the present study.

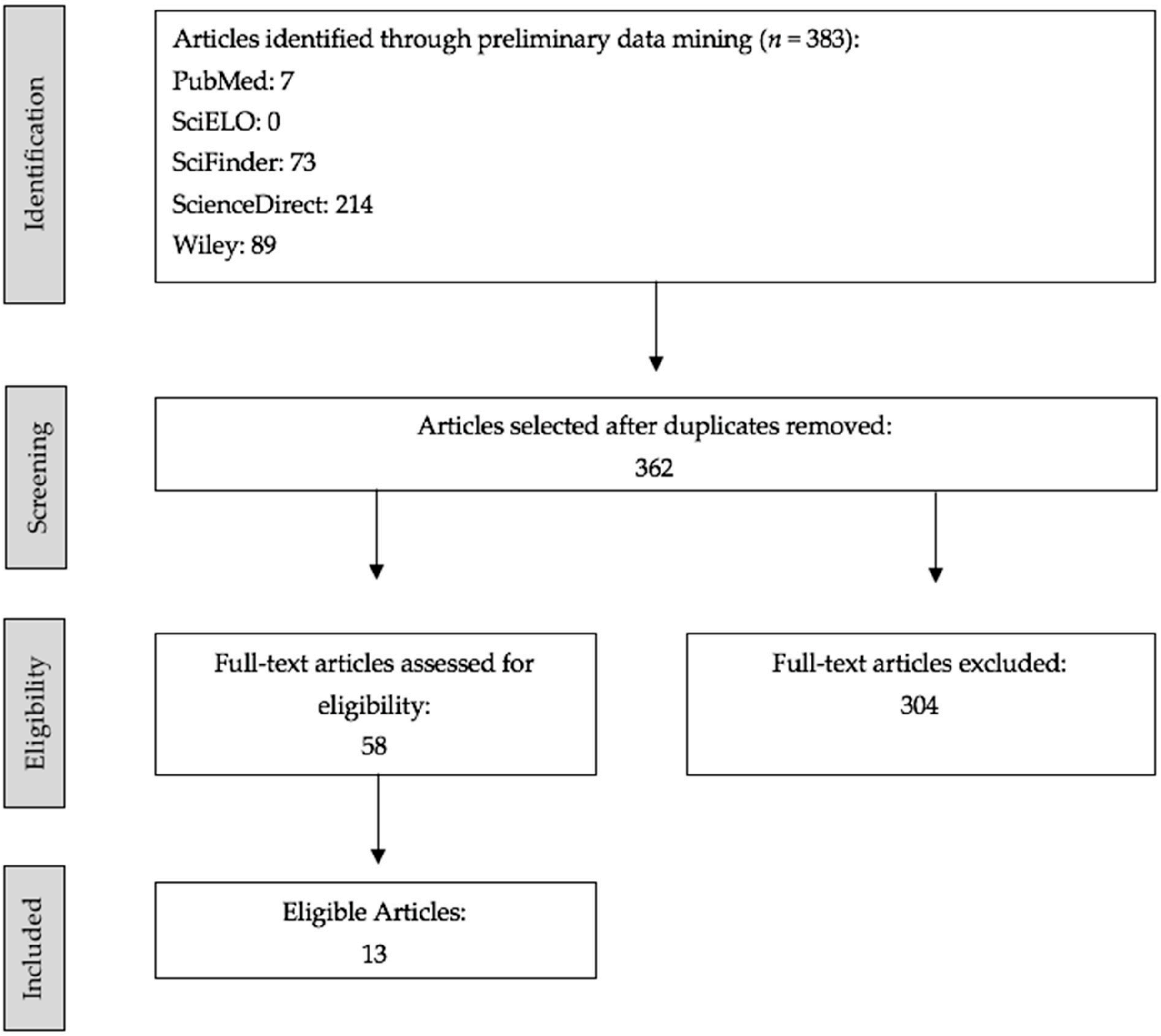

Figure 2. Flowchart showing the methodology and selection process used in the present review.

3. Results

3.1. Geography and Focus of the Studies

As reported in the Materials and Methods section, the selection criteria allowed us to collect 13 articles covering a period between 2004 and 2020. India was the country in which the greatest number of studies was performed (4), followed by Brazil and China (2) and finally Cameroon, Egypt, Mexico, Nigeria, Romania, and Thailand (1).

Several Fusarium species were investigated, and we counted nine, four, three, one, and one experiments concerning the species *F. oxysporum*, *F. moniliforme*, *F. graminearum*, *F. nivale*, and *F. verticillioides*, respectively.

3.2. *Z. officinale* EO Composition

All of the selected experiments were performed on the *Z. officinale* rhizome without evidence concerning specific pretreatments; the preferred extraction method was found to be hydro-distillation by a Clevenger-type apparatus. Regarding the essential oil composition, α-zingiberene, geranial, and ar-curcumene were reported seven, four, and three times, respectively, in the top three compounds of the essential oil (Table 1). In accordance with [32], α-zingiberene and ar-curcumene were the major components of *Z. officinale* EO; these two compounds represented a percentage of the total EO content that ranged from 17.4% to 25.4% and from 14.1% to 16.4%, respectively. Even if the biological activity of essential oils may be attributed to the chemotype and the synergy between different components, these particular molecules nevertheless deserve attention in further research. However, the amount and the composition of the bioactive substances may vary according to different factors such as the harvest time; the climatic, geographic, and growing conditions; the extraction methods; etc. [32]. A research study from Sri Lanka [33] performed in 2021 reported α-zingiberene and ar-curcumene among the main compounds of *Z. officinale* EO. The study investigated the effect of maturity stage on the weight yield of two local varieties, Rangoon and Siddha, in comparison with a Chinese variety. The authors found that the highest quantity of essential oils was evident five months after sowing and decreased in the following months. This result seems to be related to a progressive increase in the fibrous matter of the rhizome after five months, at which point the amount of essential oil begins to decrease. Concerning the chemical composition, α-zingiberene was identified in EO obtained from both varieties, but with very different results. The Rangoon variety showed data regarding α-zingiberene content levels that ranged from 9.7% to 14.2% at five and eight months, respectively. In the same post-harvest period, the amount of α-zingiberene in the Siddha variety was between 0.0% and 1.6%. *Z. officinale* EO samples obtained from Ecuador [34] showed the presence of α-zingiberene at 17.4% of total composition and geranial at 10.5%. Another study from India (Sikkim) [35] detected the presence of α-zingiberene at 16.3% and 19.8% and geranial at 8.2% and 16.5% of the total composition of two local cultivars, named Bhaisa and Majulay, respectively. In 2001, an analysis of samples of *Z. officinale* EO from S. Tomé y Príncipe [36] revealed that geranial represented 13.4–16.0% of total composition, α-zingiberene was 8.3–15.1%, and ar-curcumene was 1.5–3.4%. All of these data confirm that EO composition can be affected by several factors, such as agricultural practices, the variety cultivated, and climatic conditions. Additionally, storage conditions and pretreatments can also influence the yield and composition of EOs [34]. According to ISO 16928:2014 [37], quality standards regarding chromatographic profile have been developed that take into account three different origin areas, namely China, India, and West Africa, and the values for α-zingiberene, geranial, and ar-curcumene ranged from 29% to 45%, 5.0% to 11.0% and 0.0% to 3.5%, respectively, with some minimal differences based on the area of origin. Data related to Table 1 showed great variability, and only a few samples can be compared with the ISO standard.

Zingiberene is the molecule that is responsible for the distinctive flavor and aroma of ginger. It is a sesquiterpene hydrocarbon, and it belongs to the mevalonate pathway [38]. It has been investigated for its biological properties showing antibacterial, antifungal, and antioxidant activities [39], and there are some preliminary results on its potential as a cytotoxic agent against some cancer cell lines [40]. Currently, there are very few data concerning its potential against fungal pathogens belonging to the genus *Fusarium*. Geranial and neral, often in a ratio of 2:1, represent a mixture of two double-bond monoterpen isomers that comprise citral. According to the scientific literature [38], geranial belongs to the methylerithrytol pathway, and this occurs by the oxidation of geraniol. The isolated molecule and the mixture (citral) have been widely studied because they are commonly used as fragrance, food additive, and flavor ingredients and have been associated with potential allergenic reactions [41]. Additionally, several investigations revealed their potential as anticonvulsants [42], estrogen modulators [43], and anti-adhesion and antibiofilm compounds [44]. Finally, ar-curcumene is also a sesquiterpene hydrocarbon that participates in the typical ginger "bouquet" and has been investigated for its antibacterial properties [32,45], apoptotic effects on SiHa cells [46], and its larvicidal and oviposition deterrence activity [47]. Therefore, our findings revealed a lack of studies relating to the activity of the above-mentioned compounds against *Fusarium* spp., even though they are widely present in many essential oils.

Table 1. Antifungal activity of *Z. officinale* essential oil against *Fusarium* spp.

Country	Extraction Method/Distillation Time (h)	Main Compounds	MIC/% Inhibition Rate/Zone Inhibition	Assay	*Fusarium* Species	Positive Control	Negative Control	Refs.
Brazil	HD/2	α-Zingiberene (22.94%), α-citral (13.58%), geranial (10.39%)	>2000 μg/mL	Broth dilution method	*F. graminearum*	n.r.	Fungal inoculum with no essential oil	[1]
Brazil	HD/2	α-zingiberene (23.85%), geranial (14.16%), (E,E)-a-farnesene (9.98%)	2500 μg/mL	Broth dilution method	*F. verticillioides*	n.r.	Fungal inoculum with no essential oil	[5]
Cameroon	HD/n.r.	n.r.	500 ppm	Agar dilution technique	*F. moniliforme*	n.r.	Fungal inoculum with no essential oil	[48]
China	n.r.	α-Zingiberene (31.47%), Beta-sesquiphellandrene (13.76%), alfa-curcumene (10.41%)	61.4% (280 μL)	Puncture inoculation method	*F. oxysporum*	n.r.	Fungal inoculum with no essential oil	[49]
Egypt	HD/3	β-sesquiphellandrene (27.16%), caryophyllene (15.29%), zingiberene (13.97%)	75 μg/mL	Broth dilution method	*F. oxysporum*	Amphotericin B	Fungal inoculum with no essential oil	[50]
India	HD/n.r.	Geranial (25.9%), α-Zingiberene (9.5%), (E,E)-alpha-farnesene (7.6%)	100% 6 μL)	Inverted Petri plate technique/Poison food technique	*F. moniliforme*	n.r.	Water	[51]
India	HD/6	α-Zingiberene (28.62%), camphene (9.32%), *ar*-curcumene (9.09%)	62.5% (10 μL) 87.5% (10 μL) 75.0% (10 μL)	Poison food technique	*F. graminearum* *F. oxysporum* *F. moniliforme*	n.r.	Medium without EO	[52]
			42.8% (10 μL) 50.0% (10 μL) 85.7% (10 μL)	Inverted Petri plate technique	*F. graminearum* *F. oxysporum* *F. moniliforme*			
India	HD/6	1,8-cineol (27.0%)	79.5% (20% oil concentration)	Poison food Technique	*F. oxysporum*	n.r.	Medium without essential oil	[53]
India	HD/3	n.r. (*Z. officinale* EO and combination of EO *Z. officinale* + *C. longa*)	100% (2.5 μL/mL)	Broth dilution method	*F. oxysporum*, *F. nivale*	n.r.	Medium without essential oil	[54]
Mexico	HD/4	Eudesmol (8.19%), γ-terpinene (7.88%), α-curcumene (7.28%)	FC_{50} (0.10 mg/mL)	Inhibition of radial growth	*F. moniliforme*	Ketoconazole (60 μg)	Olive oil (4 μL)	[55]
Nigeria	HD/5	α-Zingiberene (18.6%), Geranial (13.9%), Neral (10.7%)	100% (5 μL/mL)	Poison food technique	*F. oxysporum*	60 μL/mL of Azoxystrobin/Difenoconazole	Medium without essential oil	[39]

Table 1. *Cont.*

Country	Extraction Method/Distillation Time (h)	Main Compounds	MIC/% Inhibition Rate/Zone Inhibition	Assay	*Fusarium* Species	Positive Control	Negative Control	Refs.
Romania	HD/n.r.	n.r.	*F. oxysporum* (DL50 = 1139 µL/L, DL80 = 1822 µL/L, DL90 = 2050, and DL95 = 2164 µL/L)	Agar dilution method	*F. oxysporum*	n.r.	Medium without essential oil	[56]
			F. graminearum (DL50 = 1199 µL/L, DL80 = 1919 µL/L, DL90 = 2158, and DL95 = 2278 µL/L)		*F. graminearum*			
Thainland	HD/24	Camphene, 1,8-cineol, and α-pinene	10.0 mg/L	Minimum inhibition concentration	*F. oxysporum*	n.r.	n.r.	[57]

n.r.—not reported. HD—hydro-distillation.

3.3. Z. officinale EO Antifungal Activity

F. oxysporum has been the most investigated species, but some preliminary results are also available for *F. graminearum* and *F. moniliforme*. Data concerning antifungal activity may be strongly influenced by assay methods, and there is wide variability in the expression of the results. Indeed, MIC values for broth dilution methods ranged from 75 to 2500 μg/mL. In addition, several studies that applied the food poison technique showed a range of inhibition zones from 62.5% to 100% using EO concentrations between 5% and 10%. The antibacterial activity of EOs has been correlated to the destabilization of the cellular architecture, mainly due to the breakdown of the membrane. Membrane rupture is linked to the leakage of cellular components that involve the inhibition of membrane transport and energy production [58]. Due to the lipophilic nature and the small size of EO molecules, EOs are able to penetrate lipid barriers; this changes the permeability of the cell membrane, and the main effect is the outflow of ions and cellular constituents [59]. A study performed by the authors of [60] against *Aspergillus flavus* reported an MIC of 0.6 μL/mL. The authors proposed as a possible antifungal mechanism the depolarization of the mitochondrial membrane and the interference of the EO with carbohydrate catabolism. Additionally, there are few studies regarding the antifungal activities of *Z. officinale* EO (Figure 3a–c); some preliminary results have been reported on fluconazole-susceptible and fluconazole-resistant *Candida albicans* strains, showing an MIC of 2500 μg/mL [61].

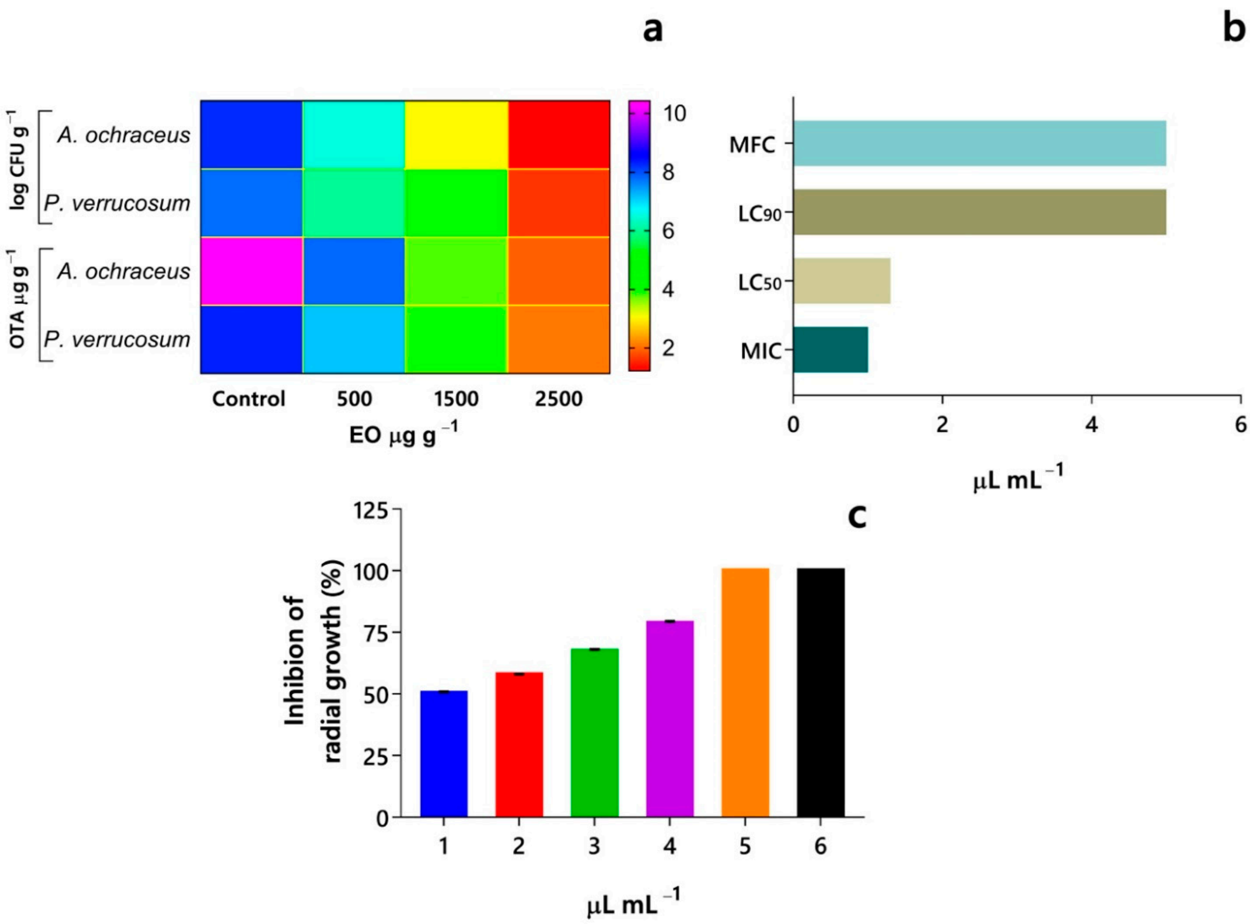

Figure 3. Microbiological effects of EOs of *Z. officinale*. (**a**) Effect of *Z. officinale* EO on growth (top) and ochratoxin A (OTA) production (bottom) in fungi in maize grains [62]; (**b**) effectiveness; and (**c**) inhibitory effect of *Z. officinale* EOs on the growth of *F. oxysporum* [39].

There are several reports on the antifungal activities of *Z. officinale* against different fungal species. The minimum inhibitory concentration (MIC, μg/mL) and the minimum fungicidal concentration (MFC, μg/mL) of EO of *Z. officinale* were found to be 1898 ± 33.41, 2621 ± 37.72 for *Aspergillus ochraceus* and 1255 ± 18.30, 1442 ± 37.81 for Penicillium verrucosum, respectively [62]. Comparatively, in the same investigation, it was found that the EOs of *Z. officinale* showed less antifungal activity than the EOs of *Cinnamomum zeylanicum* and *Cymbopogon martini*, but similar levels of antifungal activity to *Curcuma longa* and *Ocimum basilicum*. Even though the results were not consistent, increasing concentrations of ginger EO (0.5–5 × 10^3 μg/mL) decreased ergosterol production from 200–350 μg/mL to ~5 μg/mL in *Fusarium verticillioides* [5]. The antifungal activity of ginger EOs is highly species-dependent; certain fungal species are highly sensitive and some species are less sensitive to the EOs of ginger. The LC_{50} values (μL/mL) of ginger EOs against different fungal phytopathogens are as follows: *Fusarium oxysporum* (1.3), *Colletotrichum falcatum* (1.5), *Ganoderma boninense* (2.5), *Pyricularia oryzae* (2.8), *Rigidoporus microporus* (3.5), *Xanthomonas oryzae* pv. oryzae strain A (300), and *Ralstonia solanacearum* (400) [39]. Surprisingly, the rhizosphere microbiome of *Z. officinale* has also shown antifungal activity, which implies an indirect antifungal role for ginger plants. For instance, *Bacillus vietnamensis*, isolated from the rhizosphere of *Z. officinale*, was shown to inhibit *Pythium myriotylum*, which is a causative agent of Pythium rot in ginger [63]. Thus, the above insights clearly suggest that *Z. officinale* and its EO have antifungal properties that could be useful in the control of potential fungal phytopathogens.

Ultimately, even if all research confirms that *Z. officinale* EO displays promising antifungal activity against *Fusarium* species, additional studies are needed in order to investigate the above-mentioned results in the context of pre- and post-harvest activities.

3.4. Effect of Z. officinale EO on Ergosterol Production Anti-Mycotoxigenic Activity

Ergosterol determination by HPLC-UV is a widespread analytical technique used in order to quantify antifungal activity in food. Ergosterol is an indicator of fungal contamination due to its natural role as a specific constituent of mycelium cell membranes, and for this reason, ergosterol can be used as a biological marker. Moreover, ergosterol has been used as an easily detectable and accurate indicator of potential mycotoxin presence in foods [64]. The main roles of ergosterol in yeast cells are related to structural and hormonal functions, which are crucial in order to maintain and regulate the physiological development of cell membranes in microorganisms. The mode of action of some synthetic and natural antifungal agents may be explained as the inhibition of cell growth by elective interference with ergosterol biosynthesis [39].

As reported in Table 2, *Z. officinale* EO also seems to be able to inhibit the production of deoxynivalenol (DON) (Figure 4), a low-molecular-weight trichothecenes belonging to a group of sesquiterpenoids produced by *Fusarium* spp. [65]. This mycotoxin is quite widespread in crops such as corn, wheat, barley, and potatoes; it is responsible for gastrointestinal inflammation, emesis, and diarrhea in animals. In addition, humans can be affected by DON and may show similar symptoms, but chronic effects as carcinogenic, teratogenic, and immune-suppressive diseases have also been reported as the principal danger. Indeed, the World Health Organization and the Food and Agriculture Organization have recognized DON as a very critical food contaminant [66,67]. As reported by Ferreira et al. (2018) [1], significant to total inhibition of DON production may be achieved by levels of *Z. officinale* EO ranging between 500 and 2000 μg/mL, respectively.

Table 2. Ergosterol quantification and anti-mycotoxigenic activity of several *Z. officinale* EOs.

Country	Effects of EO upon Ergosterol Production (Determined by HPLC)	Anti-Mycotoxigenic Activity	*Fusarium* Species	Positive Control	Negative Control	Refs.
Brazil	Concentrations higher than 1000 μg/mL of EO caused significant inhibition	Significant reduction in DON levels by 47.3% ($p < 0.05$) at a concentration of 500 μg/mL Total inhibition: 2000 μg/mL	*F. graminearum*	n.r.	Fungal inoculum with no essential oil	[1]
Brazil	Concentrations ranging from 4000 to 5000 μg/mL caused inhibition ranging from 57% to 100%	Significant inhibition of FB1 production ($p < 0.05$) at a concentration of 4000 μg/mL and complete inhibition at 5000 μg/mL Significant inhibition of FB2 production at 2000 μg/mL and complete inhibition at 3000 μg/mL	*F. verticillioides*	Suspension of 4×10^5 CFU/mL (*F. verticillioides*)	n.r.	[5]

n.r.—not reported.

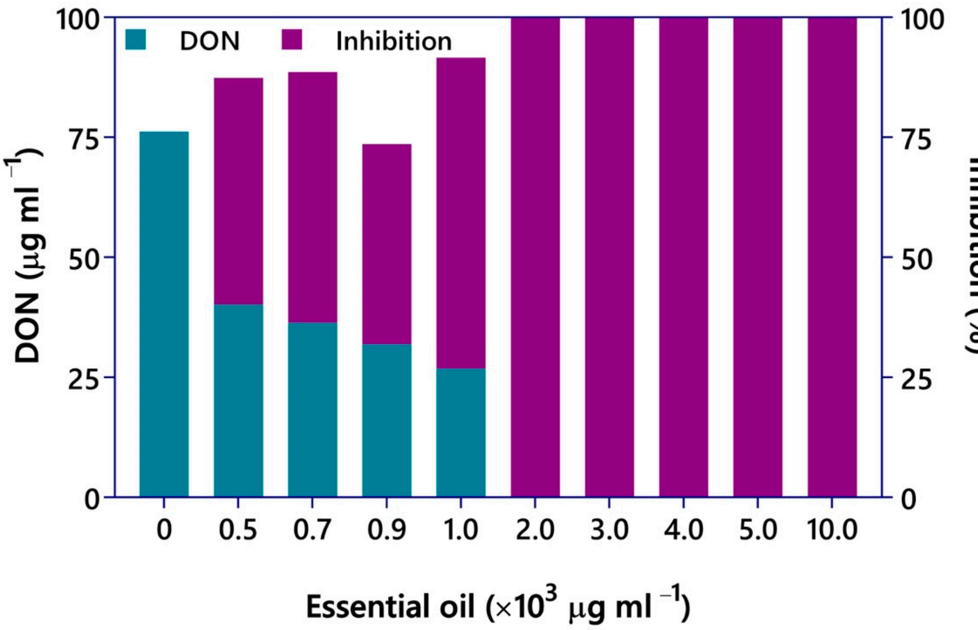

Figure 4. Relationship between *Z. officinale* EO and mycotoxin deoxynivalenol (DON) synthesis [1].

Research performed by Cai et al. (2021) [59] reported preliminary results concerning the effectiveness of EOs and herbal extracts in the reduction in mycotoxins, including AFB1, AFB2, AFG1, AFG2, DON, FB1, and OTA. Despite the fact that the degradation mechanism of mycotoxins by EOs and their components has not been clearly elucidated, this field of research deserves additional investigation. Moreover, as reported in [68] by Mirza Alizadeh et al. (2021), EOs are able to inhibit mycotoxin synthesis due to their interference with metabolic pathways and gene expression patterns in fungi.

4. Discussion

As reflected in the above-mentioned research, *Z. officinale* EO may be suggested as a potential plant-based treatment for *Fusarium* infections even if further investigations are needed. EOs are gaining more attention as promising plant-based biocontrol agents in food crop protection due to their synergic potential as anti-phytopathogenic, weed, and pest control treatments. Several studies revealed these findings in the previous decade, but the development and application of commercial products based on EOs or their components are still a long way off [7,69,70].

The application of EOs in crop protection presents advantages due to their wide-spectrum activities, their low toxicity, their lower persistence in soils and groundwater, and the reasonably low risk for non-target species, such as mammals and aquatic organisms [69,71].

Additionally, EOs are a good candidate for organic management strategies [72,73] due to the existence of several certified organic brands.

On the other hand, disadvantages have been pointed out concerning the use of EOs in crop protection, such as limited effectiveness, the need for frequent and higher application rates compared to conventional pesticides, high costs for authorization and regulatory processes, and decreased impact due to biodegradability in the field [69].

EO activity may be enhanced by nanotechnology. As reported by Kutawa et al. (2021) [74] and Adamu et al. (2021) [75], encapsulation and nanotechnology approaches seem to be able to enhance the antifungal and antibacterial activities of *Z. officinale* EOs in different crops. Abdullahi et al. (2020) [39] reported the potential application of *Z. officinale* EO in the control of tropical plant diseases, focusing on the idea that nanoemulsion may be able to improve its efficiency and bioavailability by allowing the controlled release of the EO in order to obtain a more stable and soluble biopesticide prototype. The same authors reiterated that foliar spray and irrigation techniques may enhance the activity of encapsulated EOs.

Moreover, in order to reduce *Fusarium* infections and mycotoxin contaminations, EOs may be proposed as an alternative approach to conventional fungicides, also taking into account some findings that highlighted the utility of appropriate crop rotation [76], pretreatment with salicylic acid [77], and the use of biological control agents, such as Clonostachys rosea [78] and lactic acid bacteria [79]; these methods have shown promising results against infection and mycotoxin spread. Finally, a research study performed by Madege et al. (2018) [80] determined that insecticide treatment is able to reduce *Fusarium* symptoms in maize, possibly due to an easier diffusion of *Fusarium* infection where significant insect damage is present. All of these findings, though they represent preliminary results, suggest the need for a synergistic approach to crop protection, and further investigations may reveal a new fungicide treatment or enable a reduction in conventional/synthetic fungicides.

Finally, *Zingiber officinale* represents one of the major spice crops produced in several Asian countries, such as China, India, Nepal, and Thailand, with an estimation of 1.683 thousand tons per year [81]. These data may be crucial in order to develop a commercial biofungicide and to plan adequate EO production, because a large quantity of rhizomes and organized crop production may encourage the industrial scale-up process.

With this vision, *Z. officinale* EO could play a role in a new pivot for how anti-Fusarium control is handled.

5. Conclusions

The present review article investigated some promising preliminary findings concerning the anti-Fusarium potential of *Z. officinale* EO. *Z. officinale* EO deserves a wider in-depth analysis in order to complete these discoveries, propose alternative research trends, and enable potential industrial developments. New research approaches should be adopted for the purpose of completing a general understanding of *Z. officinale* EO with respect to its anti-Fusarium activity and promoting innovative crop-protection strategies. In particular, further studies should be encouraged regarding (1) emerging nanotechnology formulations that may enhance EO activity (nanoemulsion, nanoparticles, etc.); (2) additional research about anti-mycotoxigenic activity; (3) synergistic anti-Fusarium activity with conventional biocontrol agents; (4) synergistic anti-Fusarium activity with other certified-organic compounds in order to investigate alternative organic management strategies; (5) investigations that relate phytochemistry with bioactivity (e.g., bioautographic investigations); and (6) new toxicological evaluations of long-term and acute toxicity in mammals and aquatic organisms, as well as evaluations of environmental impact and biodegradability.

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