Review

Curcuma longa L. Rhizome Essential Oil from Extraction to Its Agri-Food Applications. A Review

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Abstract: Curcuma longa L. rhizome essential oil is a valuable product in pharmaceutical industry due to its wide beneficial health effects. Novel applications in the agri-food industry where more sustainable extraction processes are required currently and safer substances are claimed for the consumer are being investigated. This review provides information regarding the conventional and recent extraction methods of C. longa rhizome oil, their characteristics and suitability to be applied at the industrial scale. In addition, variations in the chemical composition of C. longa rhizome and leaf essential oils regarding intrinsic and extrinsic factors and extraction methods are also analysed in order to select the most proper to obtain the most efficient activity. Finally, the potential applications of C. longa rhizome oil in the agri-food industry, such as antimicrobial, weedicide and a food preservative agent, are included. Regarding the data, C. longa rhizome essential oil may play a special role in the agri-food industry; however, further research to determine the application threshold so as not to damage crops or affect the organoleptic properties of food products, as well as efficient encapsulation techniques, are necessary for its implementation in global agriculture.

Keywords: Curcuma longa; essential oil; extraction methods; chemical composition; agri-food industry; antimicrobial; herbicidal; antioxidant

1. Introduction

Medicinal and aromatic plant species (MAPs) have been broadly exploited as food flavourings, medicinal agents, preservatives and ornaments, as well as beauty and personal delight products, becoming natural alternatives that offer reliability, safety and sustainability [1,2]. Amongst them, turmeric (Curcuma longa L., Zingiberaceae) is especially popular worldwide because of its attractive culinary, cosmetic and medicinal uses [3]. Specifically, the interest of this tuberous species resides in its exploitation as a colouring and flavouring agent, as well as in its numerous pharmacological activities, such as antioxidant, anticancer, anti-inflammatory, neuro- and dermoprotective, antiasthmatic or hypoglycaemic [4–10], being recently reported that turmeric can even potentially contribute against the life-threatening viral disease COVID-19 by inhibiting the main protease enzyme [11]. Most of these interesting features and properties principally come from the rhizome [3,12], a horizontal underground stem from which the shoots and roots arise [13]. It has distinctive organoleptic properties: a yellow/brown colour externally, with a deep orange inner part, a special aromatic smell and a bitter, hot taste. These characteristics make C. longa rhizome ideal for gastronomy. Especially, it is the principal ingredient of curry, for which it is probably popularly known [14–16].

Furthermore, rhizomes are a rich source of two major products with remarkable attributes: curcuminoids and essential oils [17]. On the one hand, curcuminoids are the responsible for the previously described orange-yellow colour [15]. They particularly refer to a group of three phenolic compounds, curcumin, demethoxycurcumin and bis-demethoxycurcumin, belonging to the diarylheptanoid family. They consist of a diketonic...
hydroxycarbon skeleton with different functional groups, depending on the curcuminoid [18,19]. Their content in the *C. longa* rhizome may vary according to many factors, such as the variety and geographic location, as well as cultivation and postharvest processing conditions [17,20]. For these secondary metabolites, turmeric is commonly employed as a spice and additives that provide colour and flavour in the food industry [21]. Additionally, they have demonstrated promising antioxidant and anti-inflammatory activities, being considered a valuable complementary therapy to pharmaceuticals in Crohn’s, diabetes and cancer between other disorders [15,21,22]. Unfortunately, their poor solubility, low absorption and bioavailability, as well as high metabolic rate, limit their use for therapeutic purposes [23–26]. In fact, the major component curcumin has not been approved as a therapeutic agent yet due to its pharmacokinetics and physicochemical properties, despite it is generally considered a safe substance [24,27]. In response, curcuminoids have been associated with lipids, micelles, nanoparticles and other molecules to enhance their effects. An example is the binding of curcumin with phosphocaseins. This combination represents a suitable vector to deliver efficiently the compound, as well as other drugs and nutrients in general. New analogues with improved activity are being tried to develop from the original ones [21,28–32].

On the other hand, the essential oil is the one that provides the *C. longa* rhizome a particular spicy and aromatic flavour [3,15] with its distinctive chemical composition. In general, sesquiterpenes are the predominant phytochemical group in *C. longa* rhizome oil [33]. More concretely, ar-, α- and β-turmerones are usually the major and most representative components [34,35], although numerous intrinsic and extrinsic elements may influence in their quality and quantity [36–41]. Nevertheless, this chemical composition is different from the essential oil extracted from the aerial parts in which monoterpenes (α-phellandrene, terpinolene, 1,8-cineole, etc.) stand out [42–46]. Countless beneficial health effects have been attributed to *C. longa* rhizome oil as a consequence of this particular chemical composition: cardiovascular protection, antihyperlipidemic, antiglycaemic, antioxidant, antiplatelet, anti-inflammatory, antioxidant, antiarthritic, etc. [47]. Especially, abundant research has been focused on ar-turmerone, demonstrating its promising interesting medicinal properties, like the protection against the development of certain tumours [48,49], antifungal activity against dermatophytes [50], antiangiogenic effects [51], anticonvulsant properties [52] and treatment of neurodegenerative and other inflammatory diseases, such as psoriasis [53,54].

Nowadays, there is a growing demand of essential oils in the perfume and cosmetics, agriculture, pharmacy, food and beverage, as well as in many other, industries. One of the principal aims is to replace synthetic products with detrimental health and environmental effects [55]. In particular, numerous essential oils such as winter savoury, peppermint, oregano, wintergreen and eucalypt, as well as many of their principal components (carvacrol, limonene, etc.) have already exhibited attractive and useful antimicrobial, herbicidal and antioxidant activities for the agri-food industry [56–62]. These data favour their potential use as natural preservatives to prevent the crop and food spoilage and extend the shelf-life, as well as weed control without significantly affecting the harvests.

The medicinal and culinary properties of *C. longa* rhizome oil are well-known. However, its potential applications in the agri-food industry are still under investigation. Therefore, the attempt of the present review is to present detailed literature dealing with the extraction, chemical composition and biological activity of *C. longa* rhizome essential oil in order to highlight the potential application in the agri-food industry as natural, safer and more sustainable antimicrobial, herbicidal and antioxidant agents. Specifically, the different possible extraction methods of the essential oil from the rhizomes *C. longa* and their characteristics will be discussed first. Then, the qualitative and quantitative chemical compositions of *C. longa* rhizome oil and the factors that influence it, as well as the difference with other parts of the plant and other *Curcuma* spp. will be described. Finally, the antimicrobial, herbicidal and food preservative properties of *C. longa* rhizome oil will also be discussed to assess a prospective application in the emergent “bio” agri-food industry.
2. Extraction Methods to Obtain Essential Oil from *C. longa* Rhizomes

The characteristic aroma of turmeric’s rhizomes is provided mainly by its essential oil, representing an excellent marker of quality of this spice and its derived products. Several extraction processes have been carried out with the subterranean plant stems to obtain this mixture of flavouring compounds, steam distillation being the most commonly chosen one [63–65]. In this process, a blast of steam goes through the plant material placed on a perforated plate above, dragging the organic compounds [66,67]. It presents certain disadvantages on an industrial scale (Table 1), including the huge amounts of raw material and time required and, consequently, the high price [68]. In addition, this process can present difficulties sometimes, either the evaporation of the steam-volatile compounds by the remaining latent heat or the collapse by their excessive elevation in the flask [69,70]. With the aim of avoiding these drawbacks and consequently increasing the quality and quantity of the essential oil, this technique has usually been modified and/or combined with others. For instance, Chandra et al. incorporated a continuous water circulation process to the regular steam distillation of the essential oil of turmeric rhizomes and leaves, achieving 13% and 29% more yield, respectively, compared to the conventional process [71]. Moreover, a subsequent distillation with vacuum allows a more efficient extraction of turmeric monoterpenes and sesquiterpenes [72]. The addition of a packed bed of turmeric rhizomes above the steam source has been also key to maximize the essential oil yield [73]. In general, a steam jacket is formed, helping reach a constant elevated temperature of the distillation and avoiding the degradation of the oil and, therefore, the unwanted odours that emerge from it [73,74] (Table 1).

On the other hand, hydrodistillation is also widely employed in the extraction of the essential oils from turmeric rhizomes on an industrial scale, due to its low-cost efficiency and easy implementation [75]. Unfortunately, it may sometimes mean longer extraction times and the production of wastewater, as well as loss and alteration in the composition of essential oils because the raw material is in contact with the boiling water [74,75]. Despite this, distillation in the Clevenger apparatus gives better results in the deodorisation process of turmeric relative to other distillation methods, such as distillation using the Kjeldahl apparatus or under high vacuum [76].

The most recent extraction methods appear to overcome the limitations of the conventional ones, such as heat transfer, time and quality of the resulting essential oil [77,78]. These advantages have also been observed in the extraction of oleoresins and, more particularly, curcuminoids, active components of the dried rhizome of *C. longa* extracts [79–81].

Amongst these methods, supercritical fluid extraction (SFE) [65,70,82] has shown many advantages for the extraction of essential oils on an industrial scale, including the reduction of extraction times, higher quality extracts and, principally, the use of carbon dioxide (CO$_2$) as a nontoxic, non-flammable and free-of-residues solvent [74,83–85]. In relation to turmeric, superior yields but no significant differences in the relative composition or higher concentrations of most of the essential oil components [79] were obtained using SFE rather than the conventional systems of steam distillation and ultrasound extraction. However, the turmeric oil yield was higher with Soxhlet extraction than SFE [86,87]. Particularly, the combination of 320 K and 26 MPa gives an optimum production of turmeric oil with 71% turmerones’ purity [88] or 67.7% with 313 K and 20.8 MPa [89]. Similar optimal conditions to obtain the highest-quality essential oils from turmeric rhizomes (75% of α-, α- and β-turmerone) were reported by Carvalho et al. (333 K and 25 MPa) [90]. Nevertheless, this technique is still under study to achieve a higher optimization. The influence of the variation of different operating parameters (temperature, extraction time, pressure, solubility and particle size) together with the integration of other techniques, such as SFE assisted by pressing (SFEAP), are investigated to reach higher yields, the quality of turmeric essential oil and its main compounds [82,83,91,92] (Table 1).

Among SFE, subcritical water extraction (SWE) also demonstrated many advantages over traditional methods in the recovery of bioactive compounds from plants, excepting implementation on the industrial scale for the moment [93]. Specifically, it takes advantage
of the special properties of supercritical water under high temperature and pressure conditions (100–374 °C, >50 bar) to extract nonpolar compounds [94]. After a deep study of the influence of operating conditions in the extraction of C. longa essential oil from rhizomes (temperature, flow rate, particle size, time, etc.), SWE has demonstrated its selectivity to enhance a target compound and its suitability as a green and effective method for the extraction of essential oil and curcumin from turmeric rhizome [86] (Table 1).

Table 1. Different extraction methods to obtain Curcuma longa essential oil: advantages and limitations. SFME: solvent-free microwave extraction, MAE: microwave-assisted extraction, HDAM: hydrodistillation assisted by microwave, SDAM: steam distillation assisted by microwave, VMHD: vacuum microwave hydrodistillation and MHG: microwave by hydrodiffusion and gravity. ↑: Increase, ↓: Decrease.

| Extraction method | Advantages | Limitations |
|-------------------|------------|-------------|
| Steam Distillation | • Can be modified and/or combined with other techniques to maximize the yield and efficiency, e.g., ↑13–29% yield | • Huge amounts of raw material needed • Time-consuming • High price • Evaporation of steam-volatile compounds and even collapse |
| Hydrodistillation | • Low-cost efficiency • Easy implementation • Clevenger gives better deodorization results than other processes | • Long extraction times • Production of wastewater • Loss and/or alteration in the composition of essential oils |
| Supercritical Fluid Extraction | • Reduction of extraction times • Higher quality extracts • CO₂ as nontoxic, non-flammable and free-of-residues solvent • Superior yields | • No significant differences in qualitative and quantitative composition of turmeric essential oil with respect to other methods: 67.7–75% turmerone purity at 313–320 K and 20.8–26 MPa • Under study to achieve higher optimisation |
| Subcritical Water Extraction | • Especially useful to extract non-polar compounds • Selective to enhance a target compound • Green and effective to extract the essential oil and curcumin | • Low implementation in industry currently |
Table 1. Cont.

| Extraction Method          | Advantages                                                                 | Limitations                                                                 |
|----------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Ultrasonic Extraction     | • Improved mass transfer between plant cell and solvent                      | • ↓ Costs                                                                  |
|                            | • Combination with other techniques: ↑ efficiency, ↓ processing time, ↓ costs | • ↓ Extraction times                                                       |
|                            |                                                                            | • ↓ Energy consumption                                                     |
|                            |                                                                            | • ↓ CO2 emissions                                                          |
|                            |                                                                            | • Combination with other techniques to improve the performance: HDAM, SDAM, VMHD, MHG |
|                            |                                                                            | • ↓ Extraction time from 4 h of hydrodistillation to 1 h                   |
|                            |                                                                            | • No degradation products                                                  |
| Microwave Energy (SFME, MAE)| • Overcomes the problem of excessive heat; avoids the loss of compounds and properties of the essential oil | • Maximum yield                                                            |
|                            | • Suitable and safe extractants: chloroform and freons                      |                                                                            |

Ultrasonic extraction is another method of extraction of essential oils and other bioactive compounds [77,95]. It is based on ultrasonic cavitation: a bubble implosion produces micro-jets that destroy the lipid glands in the plant cell tissue, releasing the essential oil [68]. It has overcome low extraction kinetics and yields of SFE-resulting essential oils by enhancing the mass transfer between the plant cell and solvent [68,95]. Moreover, it is usually combined with other extraction techniques, enhancing the efficiency and reducing the processing time and costs [68,95] (Table 1).

The use of microwave energy (solvent-free microwave extraction (SFME) and microwave-assisted extraction (MAE)) shares similar advantages as the previous cases: a reduction of costs, extraction times, energy consumption and CO2 emissions [96]. A microwave reactor is the source of heat that promotes the bursting and release of accumulations of essential oils [97]. It represents a more efficient method for extraction of essential oils from the Zingibereaceae family, because it is able to reduce the extraction time from four h in hydrodistillation to one h, avoiding the formation of degradation products and obtaining the maximum yield [97]. Furthermore, the use of microwave extraction gives rise to other categories of techniques to improve its performance, such as hydrodistillation assisted by microwave (HDAM), steam distillation assisted by microwave (SDAM), vacuum microwave hydrodistillation (VMHD) or microwave by hydrodiffusion and gravity (MHG) [96,98] (Table 1).

Finally, solvent extraction was also used for the extraction of C. longa essential oil. It overcomes the problem of excessive heat reached with certain conventional techniques and, consequently, avoids the loss of the compounds and properties of the essential oil [99]. Ethanol, hexane or chloroform are some of the solvents used to extract turmeric essential oil, being the last one with which a higher yield of turmeric essential oil was obtained [100]. Recently, a group of researchers proposed freons as suitable and safe extractants of the essential oil from the roots of C. longa and its main components [101] (Table 1).

In general, the result is a yellow to orange-coloured liquid having a fresh, peppery and aromatic odour with sweet orange and ginger notes and a sharp and burning bitter
taste [63,64]. These physical characteristics, as well as the chemical composition and related properties of the essential oil, may vary depending on the extraction technique. For this reason, the selection of both the most adequate method and operating conditions is key to obtain the maximum amount and quality of the C. longa essential oil [17]. Together with the extraction method, other factors such as drying and storage processes also influence the chemical composition of turmeric essential oil, being necessary the subsequent identification of the chemical composition to identify the variations and the quality control of turmeric essential oil.

3. Chemical Analysis of the Essential Oil Obtained from C. longa Rhizomes

The chemical composition of the essential oil obtained from C. longa rhizomes has been widely determined through gas chromatography-mass spectrometry (GC-MS) (Table 2), which is normally used for a sesquiterpenoid analysis [102] alone or combined with gas chromatography-flame ionisation detector (GC-FID) [103–105] to achieve a quantitative analysis. The determination of the chemical composition is key, because the components of the essential oil and their concentration can be considered a fingerprint conferring specific characteristics and properties [106].

As a general rule, oxygenated sesquiterpenes have been identified as the predominant ones (Table 2) and the principal reason of the biological activity of turmeric essential oil [107]. Concretely, turmerones (α-, β- and ar-) represent the major and the most distinctive individual components [108,109] (Table 2 and Figure 1). They give interesting properties to C. longa essential oil, such as anticancer, anti-inflammatory, antioxidant and the prevention of dementia [72,110–113]. Even they enhance the bioavailability and activity of other important turmeric components like curcumin [114–116]. In particular, ar-turmerone (6S-2-methyl-6-(4-methylphenyl) hept-2-en-4-one) has been identified as the leading one, followed by α- and β-, in C. longa rhizome oil (Table 2). Many authors have reported about the therapeutic potential of ar-turmerone and its numerous benefits for human health [113]. Lee demonstrated its antibacterial activity against human pathogens like Clostridium perfringens and Escherichia coli [117]. In the same year, he also reported a higher inhibitory effect than aspirin in platelet aggregation induced by collagen and arachidonic acid [118]. Other researchers have proposed ar-turmerone as a natural anti-cancer and cancer-preventive agent, being considered the α,β-unsaturated ketone of the molecule, the principal pharmacophore, for this activity [51,119–121]. ar-Turmerone has also been observed as useful in the prevention and attenuation of inflammatory diseases like psoriasis and neuronal ones [122,123].

Figure 1. Main compounds found in the rhizomes and leaves of turmeric essential oils.
Oxygenated sesquiterpenes also constitute the predominant group in the essential oils obtained from the rhizome of other species included in the genus *Curcuma* [124]. For instance, curzerenone was the main compound in the rhizome oil of *C. angustifolia* and *C. zedoaria*; curdione was the major one in *C. nankunshanensis, C. wenyujin* and *C. kwangsiensis*; germacrone in *C. sichuanensis* and *C. leucorrhiza*; β-elemone in *C. nankunshanensis* var. *nanlingensis*; xanthorrhizol in *C. xanthorrhiza* and velleral in *C. attenuata* [124–128]. Turmerones are normally present, being considered the most representative components in general. Nevertheless, their amount may vary between species, probably due to the intrinsic differences between them [129]. The quantification of oxygenated sesquiterpenes, together with the identification of the secondary components, are key for the distinction and quality control of *Curcuma* spp. [17,130].

The sesquiterpenoids are generally followed by smaller quantities of sesquiterpene hydrocarbons in *C. longa* rhizome oil (Table 2 and Figure 1). This group is characterised by great structural diversity, providing a variety of fragrances and characteristic aromas to the essential oil [131]. Specifically, monocular bisabolane derivatives with a C9-ring formed in analogy to the menthane skeleton highlighted in turmeric essential oil obtained from rhizomes. Some examples are bisabolene isomers (β-bisabolene), α-zingiberene and ar-curcumene, characteristic of *Curcuma* spp. and ginger. β-caryophyllene is also common, widely spread in food plants and derived from α-humulene, with a C9-ring fused to a cyclobutane ring [132]. Sesquiterpene hydrocarbons predominate over oxygenated ones in the rhizome oil of other *Curcuma* spp., such as *C. aromatica* (Sesquiterpene Hydrocarbons (SH): 8.30% ± 1.90% and Oxygenated Sesquiterpenes (OS): 7.10% ± 2.14%) and *C. kwangsiensis* var *nanlingensis* (SH: 9.76% ± 1.89% and OS: 6.80% ± 1.27%) [124].

The amount of monoterpane hydrocarbons and oxygenated monoterpenes are usually lower in most samples of rhizome essential oil of *C. longa* (Table 2). Contrarily, they constitute the most abundant group in the rhizome oil of other different *Curcuma* spp., such as *C. amada* [133], as well as in the essential oils obtained from the aerial parts of *C. longa* [17,134–137]. Regarding this, the yield of *C. longa* essential oil varied between the leaves (23%), rhizomes (48%) and rhizoids (27%), and the chemical composition was different between the leaf petiole, lamina and rhizoid oils (myrcene, *p*-cymene, etc.) compared to the stem and rhizome ones in which turmerones predominated [138]. α-Phellandrene, terpinolene and 1,8-cineole (Figure 1) are usually the most abundant compounds detected in the essential oil extracted from the leaves of *C. longa* [36,39,43,44], whereas turmerones are found in minor concentrations (Table 2) [109], being also usually found in the essential oils of the aerial parts of *C. longa* *p*-cymene, α-terpinene, *myrcene* and *pinenes* (Table 2) [134,135,137,139,140]. However, in samples of *C. longa* grown in Nigeria, the leaf essential oil was dominated by turmerones, like in rhizomes (Table 2) [141,142]. In addition, important concentrations of *C*. α-aldehyde (20.58%) were found in the essential oil of *C. longa* leaves in a high-altitude research station in Odisha, India [140]. The concentration of these compounds can be increased by enhancing the leaf biomass production [143].

The aerial parts of *C. longa* normally end as waste products. An interest approach is their recycling to obtain biologically active compounds. In this sense, *C. longa* leaf essential oil and its principal component α-phellandrene have demonstrated remarkable insecticidal activity against *Cochliomyia macellaria*, causative agents of myasis in humans and animals, as well as against *Lucilia cuprina* [144,145], being also a *C. longa* leaf essential oil highlight because of its medicinal and food-preservation properties, with a significant inhibition of microbial growth and toxin production [146,147].

On the other hand, several studies corroborate that the qualitative and quantitative chemical compositions of turmeric rhizomes essential oil may fluctuate according to many factors [124,148,149]. Sometimes, different chemical compositions come from the intrinsic characteristics of each genotype. In fact, certain traits of a specific variety of *C. longa* can influence the content of rhizome oil, representing good criteria for the selection of high-yield ones. Regarding this, an interesting study observed a direct relationship between plant height and rhizome oil content, as well as a negative correlation between the amount of
essential oil in the dry leaf with the one contained in the fresh rhizome [150]. A clear example of genotype influence is the dissimilar chemical composition between yellow C. longa rhizome oil rich in oxygenated sesquiterpenes (ar-turmerone, turmerone, curlone, etc.) and red one with oxygenated monoterpenes (carvacrol, citral, methyl eugenol, geraniol, etc.) as principal compounds more similar to Origanum or Thymus spp. [151]. Indeed, the rhizome colour is closely related to the beneficial properties of C. longa [152]. The influence of the genotype or cultivars have also been reported by other authors who observed significant variations in the yield and chemical composition of rhizome oils of C. longa under similar climatic conditions [153–155].

Together with the genetic and environmental factors, the geographic location contributes to the different yields and quality of C. longa rhizome oils, even developing different chemotypes [39,109]. In India, the region of production determines the type of turmeric [156]. Samples from Nepal included α- and β-turmerones (8.19% and 17.74%, respectively) between other compounds like epi-α-patshutene (7.19%), β-sesquiphellandrene (4.99%), 1,4-dimethyl-2-isobutylbenzene (4.4%), (±)-dihydro-ar-turmerone (4.27%) and zingiberene (4.03%) [33]. The main components of the essential oil from Nigeria were ar-turmerone, α-turmerone and β-turmerone [141,157], while turmerones (approximately 37%), together with terpinolene (15.8%), zingiberene (11.8%) and β-sesquiphellandrene (8.8%), predominated in the rhizome oil from Reunion Island [134]. Turmerones still are also the predominant compounds in samples from Faisalabad (Pakistan) and Turkey [104,158]. In the South American continent, the essential oil isolated from rhizomes grown in Ecuador was rich in ar-turmerone (45.5%) and α-turmerone (13.4%), similar to Colombian samples, while that from Brazil was dominated by zingiberene (11%), sesquiphellandrene (10%), β-turmerone (10%) and α-curcumene (5%) [105,107,159].

The analysis of each C. longa habitat’s conditions can help to predict the features of the resulting essential oil and enhance its yield and quality; what results especially important for its optimisation and commercialisation. Altitude, humidity, rainfall, temperature, soil pH, organic carbon, nitrogen, phosphorous and potassium are some of the factors that lead to wide variations in the yield and chemical composition of rhizome essential oil. From the development of predictive models and in vivo tests, the altitude, soil pH, nitrogen and organic carbon have been observed as enhancers of rhizome essential oil production. Amongst them, nitrogen and organic carbon raise the turmerone content concretely and phosphorous and potassium the oil yield [40,160–162]. Land configurations involving furrows and thatches surrounding C. longa reduce the loss of these soil nutrients, enhancing the rhizome yield [41].

The stage of maturity of C. longa rhizomes can also influence in the yield, chemical composition and properties of the essential oil. In relation to this, Garg et al. demonstrated that the percentage of the essential oil content widely varied between fresh and dried rhizomes of 27 accessions of C. longa in North India [163]. Similarly, Sharma et al. also observed certain variations in the qualitative and quantitative chemical compositions between the essential oils extracted from a mix of 5–10 month-old rhizomes and eight ones [139]. Furthermore, Singh et al. confirmed that fresh rhizome essential oil contained a major quantity of the active compound turmerone than dry ones, consequently having stronger activity [164]. A different trend was observed by Gounder et al., who reported the higher activity of cured (fresh rhizome boiled in water, dried in shade and polished) and dried rhizome oils over fresh ones [165], probably due to the lower percentage of ar-turmerone and β-turmerone. Anyway, the control of the drying conditions constitutes an important parameter in order to obtain the highest content of essential oil in the minimum time possible [166,167]. The sun and mechanical drying coexist as drying methods of C. longa rhizomes [156]. In particular, Monton et al. confirmed that one hour of microwave drying without conventional drying represented the optimum conditions to obtain the highest content of turmeric essential oil [167].
Table 2. Main components of *C. longa* essential oil according to the part of the plant used, origin, method of extraction and analysis. GC-MS: gas chromatography-mass spectrometry, CG-FID: flame ionisation detector, SFE: supercritical fluid extraction, SWE: supercritical water extraction and: CG-FTIR: gas chromatography-Fourier-transform infrared.

| Part of Turmeric | Origin | Method of Extraction | Analysis | Yield | Main Components | Ref. |
|------------------|--------|----------------------|----------|-------|-----------------|-----|
| Powdered rhizomes | Nepal  | Hydrodistillation Clevenger | GC-MS | 3.0%  | β–turmerone (17.74%), α-turmeron (8.19%), cpi-α-patschutene (7.19%), β–sesquiphellandrene (4.99%), 1,4-dimethyl-2-isobutylbenzene (4.4%) | [33] |
| Pulverized rhizome | India  | Steam distillation + vacuum distillation | GC-MS | 1.6–46.6% | Turmerones, l-zingiberene, β–sesquiphellandrene, ar-curcumene | [72] |
| Rhizomes         | Brazil | Hydrodistillation assisted by microwave (HDAM) | GC-MS | 0.6%  | ar-turmerone (50.37 ± 0.99%), β–turmerone (14.39 ± 0.33%), ar-curcumene (6.24 ± 0.21%) | [98] |
| Rhizomes         | Brazil | HDAM + Cryogenic grinding (CG) | GC-MS | 1.00% | ar-turmerone (47.97 ± 1.19%), β–turmerone (13.70 ± 0.55%), ar-curcumene (5.94 ± 0.27%) | [98] |
| Rhizomes         | Brazil | Steam distillation assisted by microwave (SDAM) | GC-MS | 0.9%  | - | [98] |
| Rhizomes         | Brazil | SDAM + CG | GC-MS | 1.45% | - | [98] |
| Powdered dried rhizome | Serbia | Hydrodistillation Clevenger | GC-MS and GC-FID | 0.3 cm³/100 g | ar-turmerone (22.7%), turmerone (26%) and curlone (16.8%) | [104] |
| Rhizomes         | Pakistan | Hydrodistillation | GC-MS | 0.673% | ar-turmerone (25.3%), α-turmerone (18.3%) and curlone (12.5%) | [158] |
| Powdered rhizomes | Thailand | Hydrodistillation Clevenger | GC-MS | - | ar-turmerone (43–49%), turmerone (13–16%) and curlone (17–18%) | [166,167] |
| Dried rhizomes   | Brazil | SFE | GC-MS | 0.5–6.5 g/100 g | ar-turmerone (20%) and ar-, α- and β–turmerones (~75%) | [91] |
| Dried rhizomes   | Brazil | Extraction with volatile solvents | GC-MS and CG-FID | 5.49% | α-turmerone and β–turmerone (~8.7%), ar-turmerone (~3.6%) | [104] |
| Dried rhizomes   | Brazil | Steam distillation | GC-MS and CG-FID | 0.46% | ar-turmerone (~12.8%), α-turmerone and β–turmerone (~4.1%) | [104] |
| Dried rhizomes   | China  | Steam distillation | GC-MS | 4.50% w/w | ar-turmerone (11.81%) | [124] |
| Dried rhizomes   | Nigeria | Hydrodistillation Clevenger | GC-MS | 1.33% w/w | ar-turmerone (44.4%), α-turmerone (20.8%), β–turmerone (26.5%) | [141] |
| Dry rhizomes     | India  | Hydrodistillation Clevenger | GC-MS | 2.9%  | ar-turmerone (21.4%), α-santalene (7.2%) and ar-curcumene (6.6%) | [164] |
| Part of Turmeric | Origin       | Method of Extraction | Analysis | Yield               | Main Components                                      | Ref.  |
|-----------------|--------------|----------------------|----------|---------------------|------------------------------------------------------|-------|
| Dried rhizomes  | India        | Hydrodistillation    | GC-MS    | 3.05 ± 0.15%        | ar-turmerone (30.3%), α-turmerone (26.5%), β-turmerone (19.1%) | [167] |
| cured rhizomes  | India        | Hydrodistillation    | GC-MS    | 4.45 ± 0.37%        | ar-turmerone (28.3%), α-turmerone (24.8%), β-turmerone (21.1%) | [167] |
| Dried root      | -            | SFE                  | GC-MS    | 2–5.3 wt%           | ar-turmerone (31–67.1%), β-turmerone (2–37.9%), α-turmerone (0–21.3%) | [87]  |
| Fresh rhizomes  | Brazil       | Hydrodistillation    | GC-MS    | 1000 µL             | α-turmerone (42.6%), β–turmerone (16.0%) and ar-turmerone (12.9%) | [34]  |
| Fresh rhizomes  | India        | Hydrodistillation    | GC-MS    | 0.6–2.1%            | Turmerone (35.24–44.22%)                             | [39]  |
| Fresh rhizomes  | India        | Hydrodistillation    | GC-MS    | 0.8%                | α-turmerone (44.1%), β–turmerone (18.5%) and ar-turmerone (5.4%) | [43]  |
| Fresh rhizomes  | India        | Hydrodistillation    | GC-MS    | 0.36%               | ar-turmerone (31.7%), α-turmerone (12.9%), β–turmerone (12.0%) and (Z)–β–ocimene (5.5%) | [44]  |
| Fresh rhizomes  | India        | Modified distillation process | GC-MS | 2.09–2.50% | ar-turmerone (45.27%), curone (5.6%), turmerone (4.4%), zingiberene (4.0%), ar-curcumene (4.0%), dehydrocurcumene (2.0%) | [73]  |
| Fresh rhizomes  | Malaysia     | SFE                  | GC-MS    | -                   | ar-turmerone (10.84–21.50%), turmerone (36.14–45.68%) and curone (21.27–22.30%) | [79]  |
| Fresh rhizomes  | Iran         | SWE                  | GC-MS    | 0.98%               | ar-turmerone (62.88%), curcumin (10.49%), β–sesquiphellandrene (9.62%), α-phellandrene (6.50%) | [86]  |
| Fresh rhizomes  | Ecuador      | Steam distillation   | GC-FID and GC-MS | 0.8% v/v | ar-turmerone (45.5%) and α-turmerone (13.4%) | [105] |
| Fresh rhizomes  | France       | Steam distillation   | GC-MS and GC-FTIR | 1.1%    | α-turmerone (21.4%), zingiberene (11.8%), terpinolene (15.8%), β–sesquiphellandrene (8.8%), ar-turmerone (7.7%) and β–turmerone (7.1%) | [134] |
| Fresh rhizomes  | Bhutan       | Hydrodistillation    | GC-MS    | 2–5.5%              | α-turmerone (30–32%), ar-turmerone (17–26%) and β–turmerone (15–18%) | [139] |
| Fresh rhizome   | India        | Steam distillation   | -        | 2.03–6.50%          | -                                                    | [156] |
### Table 2. Cont.

| Part of Turmeric | Origin | Method of Extraction | Analysis | Yield | Main Components | Ref. |
|------------------|--------|----------------------|----------|--------|----------------|------|
| Dried rhizomes   | India  | Hydrodistillation Clevenger | GC-MS | 3.05 ± 0.15% | ar-turmerone (30.3%), α-turmerone (26.5%), β-turmerone (19.1%) | [167] |
| Cured rhizomes   | India  | Hydrodistillation Clevenger | GC-MS | 4.45 ± 0.37% | ar-turmerone (28.3%), α-turmerone (24.8%), β-turmerone (21.1%) | [167] |
| Dried root       | -      | SFE                  | GC-MS | 2–5.3 wt% | ar-turmerone (31–67.1%), β-turmerone (2–37.9%), α-turmerone (0–21.3%) | [87] |
| Fresh rhizomes   | Brazil | Hydrodistillation Clevenger | GC-MS | 1000 µL | α-turmerone (42.6%), β-turmerone (16.0%) and ar-turmerone (12.9%) | [34] |
| Fresh rhizomes   | India  | Hydrodistillation Clevenger | GC-MS | 0.6–2.1% | Turmerone (35.24–44.22%) | [39] |
| Fresh rhizomes   | India  | Hydrodistillation Clevenger | GC-MS | 0.8% | α-turmerone (44.1%), β-turmerone (18.5%) and ar-turmerone (5.4%) | [43] |
| Fresh rhizomes   | India  | Hydrodistillation Clevenger | GC-MS | 0.36% | ar-turmerone (31.7%), α-turmerone (12.9%), β-turmerone (12.0%) and (Z)-β-ocimene (5.5%) | [44] |
| Fresh rhizomes   | India  | Modified distillation process | GC-MS | 2.09–2.50% | ar-turmerone (45.27%), curoline (5.6%), turmerone (4.4%), zingiberene (4.01%), ar-curcumene (4.01%), dehydrocurcumene (2.0%) | [73] |
| Fresh rhizome    | Malaysia | SFE                  | GC-MS | - | ar-turmerone (10.84–21.50%), turmerone (36.14–45.68%) and curoline (21.27–22.30%) | [79] |
| Fresh rhizomes   | Iran   | SWE                  | GC-MS | 0.98% | ar-turmerone (62.88%), curcumin (10.49%), β-sesquiphellandrene (9.62%), α-phellandrene (6.50%) | [86] |
| Fresh rhizomes   | Ecuador | Steam distillation | GC-FID and GC-MS | 0.8% v/v | ar-turmerone (45.5%) and α-turmerone (13.4%) | [105] |
| Fresh rhizomes   | France | Steam distillation | GC-MS and GC-FTIR | 1.1% | α-turmerone (21.4%), zingiberene (11.8%), terpinolene (15.8%), β-sesquiphellandrene (8.8%), ar-turmerone (7.7%) and β-turmerone (7.1%) | [134] |
| Fresh mature rhizomes | Bhutan | Hydrodistillation Clevenger | GC-MS | 2–5.5% | α-turmerone (30–32%), ar-turmerone (17–26%) and β-turmerone (15–18%) | [139] |
| Fresh rhizome    | India  | Steam distillation | - | 2.03–6.50% | - | [156] |

C. longa nutrition also has a significant impact in the yield and composition of rhizome oil. Especially, fertilizer use can enhance the productivity of volatile oil of C. longa rhizomes 6% [148]. Furthermore, a prior treatment with minerals during in vitro rhizome development followed by a fertilizer treatment in a greenhouse increases the percentage of volatiles
in *C. longa* rhizomes. Particularly remarkable is the interaction of KNO$_3$ and Ca$^{2+}$, which favours the accumulation of sesquiterpenes in turmeric rhizome [168]. An interesting research proposed the use of arbuscular mycorrhizal fungi instead of chemical fertilizers in the cultivation of *C. longa* rhizomes. These optimise the absorption of nutrients and water, augment the metabolic activity of the plant, etc. In consequence, the root system becomes more robust, and the chemical composition of the essential oil is improved, increasing the production of certain compounds, including caryophyllene, α-curcumene, β-bisabolene and β-curcumene, using sustainable technologies [169,170]. Finally, the postharvest management of turmeric rhizomes also has a noteworthy influence on the quality of the derived products. Concretely, the boiling conditions, way of slicing, type of mill and speed of crushing and presence of heat and oxygen need to be controlled and standardised to obtain essential oils with certain characteristics [156].

In conclusion, the study of the chemical composition of the essential oil from the rhizome of *C. longa* gives us an idea of the characteristics and possible properties that it possesses. Sesquiterpenes are usually the main compounds in *C. longa* rhizome essential oil, highlighting the oxygenated turmerones followed by sesquiterpene hydrocarbons (Figure 1). However, the qualitative and quantitative chemical compositions of the essential oil can vary depending on the genetic and commented on factors. The knowledge of these can help to achieve a high-yield product with useful composition and properties for the agri-food industry.

### 4. Potential Applications of *C. longa* Essential Oil Obtained from Rhizomes in the Agri-Food Industry

Foodborne diseases, spoilage, insect and weed infestation are some common problems that cause significant economic losses to the agri-food industry. Chemical preservatives and pesticides have been widely exploited to maintain and enhance yields and productivity. However, the numerous handicaps derived from their overuse have been extensively described. As a result, sustainability has become an increasingly important subject in the agri-food industry. The characteristics of certain natural products, especially essential oils (zero waste), have become a matter of study as sustainable alternatives [171–176]. Amongst them, *C. longa* rhizome oil can take part in the safer and eco-friendly emergent agri-food industry due to its promising antimicrobial, herbicidal and antioxidant activities (Figure 2).

![Figure 2](image-url)  
**Figure 2.** Representation of the roles that *Curcuma longa* rhizome oil can play in the safer and more sustainable emerging agri-food industry: antimicrobial, herbicidal and antioxidant activities.
4.1. Prevention and Inhibition of Microbial Attack in Crops and Food-Spoilage Microorganisms

Microbial contamination can affect any step of the food chain, from seed germination to food processing and storage [177–180]. Initially, the seed-borne pathogens endanger the correct development of grains, affecting both yield and quality [179]. Besides, bacteria and fungi are the principal causative agents of many postharvest diseases. *Erwinia, Pseudomonas, Corynebacterium, Aspergillus* and *Fusarium* are some of the most common food spoiler species, seriously compromising the quality of food products. Moreover, human health may be disturbed by the contact with these contaminated products [181,182], along with a deleterious impact in the reliability and economics of the agri-food industry [177,183,184]. Synthetic pesticides and preservatives, some of them with detrimental effects, have been the most commonly used formulations to prevent and stop the growth of these microorganisms. Therefore, natural, safer and eco-friendly antimicrobials are demanded by the consumers [178,180,185,186]. Essential oils constitute a potential alternative, because they possess antimicrobial activity, individually or in combinations between them and with antibiotics. They prevent food deterioration, maintain their appearance and quality and are able to be used in biopreservation and biocontrol in the agri-food industry [187–191].

In general, the essential oils proceeding from the rhizomes of the genus *Curcuma* have demonstrated noteworthy antimicrobial activity [192–194]. Amongst them, the essential oil of *C. longa* rhizome with 58% of ar-turmerone, together with limonene and borneol as the principal compounds, has presented a dose-dependent antimicrobial activity against a broad spectrum of food-borne and food-spoilage bacteria and fungi, including *Bacillus subtilis, Salmonella choleraesuis, Escherichia coli, A. niger* and *Saccharomyces cerevisiae* but at higher doses than the traditional chloramphenicol and amphotericin antibiotics [195] (Table 3). The addition of *C. longa* essential oil (33.42% ar-turmerone, 22.35% α-turmerone and 20.14% β-turmerone) to an edible film with sorbitol and egg white protein powder improved both the properties of the film (thickness and lipophilicity) and its antibacterial activity against *E. coli* and *Staphylococcus aureus* [196] (Table 3).

Usually, bacterial contamination is more difficult to detect, because food generally appears normal until advanced infection. In contrast, fungal contamination can be easily perceived, as it normally alters the odour, appearance and texture of food [177,178,179]. *C. longa* essential oil has already demonstrated its strong fungicidal effect against the causal agents of important diseases in crops [192,198]. In particular, the radial growth of *Colletotrichum gloeosporioides, Sphaceloma cardamomi* and *Pestalotia palmarum* were completely inhibited after the treatment with essential oil from *C. longa* rhizomes at 1–5%. Other phytopathogenic fungi, such as *Rhizoctonia solani, Aspergillus* sp. and *Fusarium* sp., were also notably affected, especially at the highest concentration (5%) assayed [199] (Table 3).

It is interesting to note that essential oils represent a natural alternative to the usually employed weak-acid preservatives in the prevention of *A. niger*, a common contaminant of yogurt, ready-to-drink beverages and, especially, bakery products [200,201]. Particularly, packaging with a biopolymer film containing turmeric essential oil (35.46% turmerone, 20.61% cumene and 13.82% ar-turmerone) constitutes a sustainable and efficient technology to protect these food products against attacks of the filamentous fungus. The biopolymer film acts as a carrier, releasing in a sustained way the antimicrobial agent turmeric essential oil [202] (Table 3). In fact, the addition of turmeric essential oil in edible coating films could enhance food protection from microbial contamination in general. In relation to this, the fungal growth of common spoilers of pumpkin *Penicillium* and *Cladosporium* ssp. were reduced 60.3% and 41.6%, respectively, for 15 days with an edible coating based on achira starch (*Canna indica* L.) containing 0.5% w/w *C. longa* rhizome oil [203] (Table 3).

The antifungal effect of *C. longa* essential oil has been tested in other *Aspergillus* ssp., such as *A. flavus*, a common contaminant of cereals, legumes, juices, and fresh and dried fruits [182,204–208], as well as one of the major source of aflatoxins in agricultural crops, considered the most problematic mycotoxins worldwide [181,209,210]. The growth rate of *A. flavus* was significantly reduced with only 0.10% v/v of *C. longa* rhizome oil (33.2%
ar-turmerone, 23.5% α-turmerone and 22.7% β-turmerone). Furthermore, the germination and sporulation were completely inhibited at 0.5% v/v [211] (Table 3).

Regarding Fusarium spp., versatile spoilers of fruit, vegetables, cereals, etc. [212,213] generating important economic losses in the agri-food industry, C. longa rhizome essential oil has also exhibited promising results. The mycotoxin production, particularly of trichotheccenes and fumonisins, with serious health impacts in humans and livestock by their potentially carcinogenic and inhibition of the protein synthesis, respectively [214], is another problem to solve. The essential oil obtained from the fresh rhizomes of C. longa (42.6% α-turmerone, 16.0% β-turmerone and 12.9% ar-turmerone) significantly affected the development of F. verticillioides by decreasing the thickness and length of the microconidia, as well as the fungal biomass. The fumonisin production was also significantly inhibited [34] (Table 3). Likewise, C. longa rhizome oil (53.10% ar-turmerone) had a considerable effect in the morphology of the mycelia and spores, as well as in the zearalenone production of F. graminearum [215], being the mycelial growth of F. moniliforme and F. oxysporum inhibited at 1000 and 2000 ppm, respectively [192] (Table 3).

On the other hand, the essential oil obtained from other parts of C. longa with different chemical compositions has also shown antimicrobial activity. In this sense, C. longa essential oil dominated by oxygenated monoterpenes (82.0%) displayed promising in vivo antifungal activity against P. expansum and Rhizopus stolonifer when combined with A. sativum essential oil, representing a natural alternative to chemical fungicides in tomato protection [216]. Similarly, C. longa essential oil rich in monoterpenes (20.4% α-phenllandrene, 10.3% 1,8-cineole and 6.19% terpinolene) and with considerable quantities of α- and β-turmerone (19.8% and 7.35%) presented one of the highest MICs (0.06–0.36 mg/mL) with respect to 11 different essential oils against five food-spoilage yeasts [217] (Table 3).

Therefore, the high antimicrobial activity of C. longa essential oil may be due to a synergism between the usual main compounds ar-turmerone, turmerone and curlone and the other phenolic group [218].

Regarding these data, the essential oil from the rhizome of C. longa can be considered a green alternative for biopreservation in the agri-food industry. It has demonstrated promising dose-dependent antimicrobial activity against a wide range of microorganisms. This efficacy is not always shared with the essential oils extracted from other parts of C. longa. Therefore, its efficacy may be due to its particular chemical composition, especially to the predominance of turmerones and combinations with other oxygenated compounds. This makes C. longa rhizome oil the subject of incorporation in edible coating films and other encapsulating technologies for future applications.

4.2. Herbicidal Activity

The resistance and tolerance development of weeds, crop damage or environmental pollution are the main problems due to the continuous use of synthetic herbicides in global agriculture [219–221]. Alternatives to synthetic herbicides for weed management and food security require the research of natural sources such as essential oils to develop safer and more sustainable herbicides without significantly affecting crops yields. Several essential oils have demonstrated promising herbicidal properties, inhibiting seed germination and/or seedling growth of a broad number of weeds [175,222–225]. In fact, some of them are already the main components of several commercial herbicidal compositions, taking part in the construction of a harmless and eco-friendlier emergent agri-food industry [226,227].

Regarding turmeric, the rhizome essential oil (38.7% ar-turmerone, 18.6% β-turmerone and 14.2% α-turmerone) has proven to be a potential post-emergent treatment in the control of weeds such as common purslane (Portulaca oleracea L.), especially aggressive in agriculture because of its versatility in affecting a wide variety of scenarios due to its tolerance to changes and rapid growing [228,229], Italian ryegrass (Lolium multiflorum Lam.), rapidly growing weed with the capacity of producing large quantities of seeds, being particularly competitive in small grain and vegetable harvests, where it represents a
great problem due to the development of herbicide resistance [230,231] and barnyard grass (Echinochloa crus-galli (L.) Beauv.), considered one of the world’s worst weeds infesting cropping systems [232], especially detrimental in rice paddies, where it interferes with canopy light transmission, triggering a series of metabolic alterations in rice that can lead to severe losses of even 55.2% [233]. Concretely, it reduced the hypocotyl development of the three weeds 56.55%, 40.45% and 39.33%, respectively, from 0.125 to 1 µL/mL, without affecting either the seed germination or the hypocotyl growth of the tomato, cucumber and rice crops [234] (Table 3).

The harmlessness of C. longa rhizome essential oil for food crops, a great challenger in the search for natural herbicides, has been corroborated by other authors. For instance, Prakash et al. confirmed that it did not affect the germination of chickpea seeds. The mean length of both hypocotyl and radicle were not significantly reduced after three days of exposure to the essential oil regarding control (3.65 and 0.82 cm vs. 3.75 and 0.93 cm, respectively). Only its combination with Z. officinale essential oils showed certain phytotoxicity against the seeds, probably due to the activity of Z. officinale [235]. However, the essential oil proceeding from other species included in the genus Curcuma have shown phytotoxic actions against food crops. For instance, C. zedoaria essential oil with a predominance of oxygenated compounds (18.20% epi-curzerenone and 15.75% 1,8-cineole) severely depressed the germination, germination rate and seedling development of lettuce and tomatoes. Particularly, the seed germination of both crops decreased from 80% to 0% and from 100% to 40%, correspondingly, at the highest dose of C. zedoaria essential oil (1.00%) assayed, and the hypocotyl and radicle growths were significantly reduced, with the essential oil at only 0.73–0.86% [236].

Furthermore, C. longa rhizome oil constitutes a potential candidate for biological control of the emerging invasive alien plant species. Specifically, it is outstanding in the inhibitory effect in the development of pampas grass (Cortaderia selloana (Schult. & Schult. f.) Asch. & Graebn.) and tree tobacco (Nicotiana glauca Graham.) from the lowest dose (0.125 µL/mL) assayed. Among them, C. selloana exhibited a special sensitivity to C. longa essential oil. The seed germination was drastically inhibited in a dose-dependent manner, achieving 81.71% of reduction at the highest dose (1 µL/mL) applied [234] (Table 3). It is interesting to note that the management of invasive species with sustainable alternatives is another important step in global agriculture, because these species are becoming naturalized in a wide number of areas with serious consequences: they influence the environment, change soil properties, affect diversity, etc. and, finally, are reverberating in socioeconomic factors, as well as human health [237–239].

On the other hand, other products derived from C. longa have demonstrated phytotoxic activity. In this way, the Ethanolic extract completely inhibited the growth of the floating weed common duckweed (Lemna minor (L.) Griff.) at 100 and 1000 µg/mL [240], whereas the ethyl acetate extract (1000–10,000 ppm) showed the highest inhibitory effect vs. the seed germination and seedling growth of radishes in comparison to cyclohexane and n-hexane, which stimulated germination and elongation at 10,000 and 7500 ppm, respectively [241]; more recently, Akter et al. remarked on the potent inhibitory effect of the methanolic extract against the seed germination and seedling growth of both weed beggarticks (Bidens pilosa L.) and crops cress, radishes and lettuce. Especially, the major curcuminoids present in C. longa’s Ryudai gold variety strongly reduced the seed germination, as well as root and shoot growth of the weed (IC₅₀ 8.7–12.9 and 15.5–38.9 µmol/L, respectively) [242].

Therefore, C. longa can be considered an important source of bioproducts with interesting phytotoxic properties. Especially, the rhizome essential oil has demonstrated apt herbicidal activity against specific weed and invasive plant species, without significantly harming food crops. These observations make the essential oil of C. longa rhizome a reference of investigation for new weedicide compounds. Further research involving more weed and crop species, as well as different conditions, is needed to keep demonstrating its potential as a bioherbicide.
4.3. Food Decay Prevention: Antioxidant Activity

Stored food products are subject to oxidation, involving a loss of quality, alteration of the organoleptic properties and nutritional value, as well as of food safety problems. Synthetic antioxidant additives commonly used to avoid this process are under controversy currently, which has led to an increased interest in the agri-food industry to use the preservative properties of plant products.

Several essential oils and their components have already demonstrated their potential role in overcoming storage losses and enhancing food shelf-lives in the near future [243–245]. Some have even been approved as flavour or food additives, and others are under validation. Nowadays, the encapsulation of essential oils is also being studied to try to stabilise their antioxidant activity and even enhance it [246].

In general, C. longa and its products have shown their antioxidant potential as biopreservatives of physicochemical and organoleptic properties of food items, such as paneer, white hard clams, rainbow trout, cuttlefish and mashed potatoes, either alone or in combination with other plant products. This property can be improved even more with the help of nanotechnology that may control the aqueous solubility and stability of turmeric derivatives [245,247–255].

The antioxidant properties of the turmeric essential oils have been widely studied. The leaf essential oil with 22.8% β-sesquiphellandrene and 9.5% terpinolene as the main compounds has been proposed as a potential option to prevent the oxidative deterioration of fat-containing food products because of its hydrogen-donating properties and reducing power [256] (Table 3). Likewise, C. longa rhizome oil is able to decrease lipid peroxidation and other processes related to free-radical formation, achieving the extending shelf-lives of food products. In fact, it has exhibited the lowest peroxide value with respect to oleoresins and synthetic antioxidants, meaning a more efficient inhibitory effect of the formation of the secondary oxidation product malondialdehyde [164] (Table 3). This effect has been corroborated by means of diverse methods that evaluate both the scavenging capacity for different free radicals and the metal ion-chelating ability of the essential oil. Particularly, the essential oil obtained from the fresh rhizomes of C. longa (α-turmerone (42.6%), β-turmerone (16.0%) and ar-turmerone (12.9%)) has exhibited satisfactory dose-dependent DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2′-azino-bis-3-ethylbenzothiazoline-6-sulphonic acid) radical-scavenging activities (IC_{50} 10.03 and 0.54 mg/mL, respectively), as well as reducing power [34] (Table 3). Both the DPPH and ABTS methods are between the most carried out antioxidant capacity assays [257]. These are good estimators of the antioxidant activity of any extract in general, using a simple redox reaction between the antioxidant and reactive oxygen species (ROS), being considered the DPPH method as the first line for evaluating the ability of a compound and extract or other biological source to act as a free-radical scavenger or hydrogen donor because of its accuracy, simplicity and low cost [258]. On the other hand, ABTS has been observed as especially useful to track changes in the antioxidant system itself during the storage and processing steps [257]. Reducing power is usually a complementary test to the previous ones to further evaluate the antioxidant activity [259].

In this way, the antioxidant activity of C. longa rhizome essential oil stood out over 10 other different essential oils. Its free radical-scavenging potential was twice higher than that of Trolox (~60% vs. 28.2%, respectively), and the antioxidant activity (72.4%) was near the values of the reference essential oil Thymus vulgaris (90.9%) and butylated hydroxyanisole (BHA) (86.74%) [217] (Table 3). Similarly, the reducing potential of C. longa rhizome oil was also highlighted over Eucalyptus spp., such as E. sideroxylon, E. tereticornis and E. citriodora [130.5 ± 1.2, 122.1 ± 1.4 and 95.8 ± 1.0 μM ferric reducing antioxidant power (FRAP) equivalents, respectively], with 138.4 ± 1.1 μM FRAP equivalents. This value was even higher than the one of other Curcuma spp.—for instance, C. aromatica (130.6 ± 1.5 μM FRAP equivalents) [260]. This antioxidant potential has also been demonstrated in vivo. A starch/carboxymethyl cellulose (CMC) edible coating including C. longa oil suppressed the oxidase enzyme activity of fresh-cut “Fuji” apples by 9% [261] (Table 3).
The luminol-photochemiluminiscence (PLC) assay corroborated afterwards the high antioxidant activity of *C. longa* essential oil [217]. It results in an easy, fast and sensitive method to know the scavenging activity of antioxidants against the radical anion superoxide, especially for hydrophobic-like essential oils [217]. This property may be due to the total phenolic content of *C. longa* essential oil that also highlights over more than 15 essential oils from different plant species [235]. However, the phenolic compounds of *C. longa* essential oil and, consequently, the antioxidant activity can vary depending on the cultivation conditions. Especially, the substrate type, together with the presence of fungi, have significantly influenced the composition and activity of *C. longa* leaf essential oil [169,170]. The antioxidant activity can also change according to many other factors, such as the degree of dryness of *C. longa* rhizome. Specifically, the essential oil from the fresh rhizomes (24.4% arturmerone, 20.5% α-turmerone and 11.1% β-turmerone) exhibited higher DPPH radical scavenging, as well as Fe²⁺-chelating abilities, than the dry ones (21.4% arturmerone, 7.2% α-santalene and 6.6% ar-curcumene). The antioxidant activity of both essential oils was significantly higher than the commercial antioxidants BHA and butylated hydroxytoluene (BHT) [164] (Table 3). Nevertheless, other authors reported a different trend. Gounder et al. demonstrated throughout several tests that dried and cured rhizomes had higher antioxidant activity than the fresh ones (arturmerone (21.0–30.3%), α-turmerone (26.5–33.5%) and β-turmerone (18.9–21.1%)). Specifically, ABTS radical cation scavenging [Trolox equivalent antioxidant capacity (TEAC) 68.0, 66.9 and 38.9 μM at 1 mg/mL; ferric-reducing antioxidant potential (TEAC 276.8, 264.1 and 178.4 μM at 1 mg/mL); total antioxidant capacity by phosphomolybdenum assay (686, 638 and 358 ascorbic acid equivalents per 1 mg of oil) and reducing power were stronger in dried and cured rhizome than in fresh ones, respectively [165]. These differences are mainly due to the different compositions reported by the authors [164,165] in the fresh and dry rhizome essential oils used in the test.

Several research carried out with turmeric rhizome essential oil without β-turmerone among the main compounds [105,262] reported lower DPPH bleaching potential and ferric-reducing antioxidant power of *C. longa* rhizome oil (45.5% ar-turmerone and 13.4% α-turmerone) principally, in comparison to those of Trolox (IC₅₀ 14.5 ± 2.9 mg/mL vs. 0.012 ± 0.004 mg/mL and 389.0 ± 112.0 vs. 402.3 ± 20.1 μM ascorbic acid equivalents, respectively) [105], as well as negligible DPPH radical scavenging activity (38.7% arturmerone and 14.2% α-turmerone) with respect to other, different essential oils, among which were cinnamon, clove, green tea, lemon eucalyptus, rosemary, oregano and its main compound carvacrol [262] (Table 3).
| Chemical Composition | Concentration | Effect | Ref. |
|----------------------|---------------|--------|------|
| 42.6% α-Turmerone   | 16.0% β-Turmerone | 12.9% ar-Turmerone | 17.9 and 294.9 µg/mL | Decrease the development of Fusarium verticillioides by 56.0 and 79.3%, respectively, as well as the thickness and length of microconidia, fungal biomass and fumonisin production [34] |
| 51.8% ar-Turmerone  | 11.9% ar-Turmerol | 1000 ppm | Complete mycelial growth inhibition of Colletotrichum falcatum and F. moniliforme [192] |
| 51.8% ar-Turmerone  | 11.9% ar-Turmerol | 2000 ppm | Complete mycelial growth inhibition of Curvularia pallescens, Aspergillus niger and F. oxysporium [192] |
| 58% ar-Turmerone Limonene | Borneol | >45–90 µg/disc | Significant inhibition of Bacillus subtilis, Salmonella choleraesuis, Escherichia coli, A. niger and Saccharomyces cerevisiae at higher doses than chloramphenicol and amphotericin [195] |
| 33.42% ar-Turmerone | 22.35% α-Turmerone | 20.14% β-Turmerone | 1–2% (v/v) | Antibacterial activity against E. coli and Staphylococcus aureus when incorporated to an edible film with sorbitol and egg white protein [196] |
| -                    | 1–5%          |        |      |
| 35.46% Turmerone Cumene | 13.82% ar-Turmerone | >0.5 µL | Antifungal effect against A. niger when incorporated to a biopolymer film [202] |
| -                    | 0.5% w/w      |        |      |
| 33.2% ar-Turmerone  | 23.5% α-Turmerone | 22.7% β-Turmerone | 0.10–0.5% v/v | Significant reduction of the growth rate of A. flavus, as well as complete inhibition of germination and sporulation [211] |
| 53.10% ar-Turmerone | 2450 and 3300 µg/mL | Minimum inhibitory and minimum fungicidal concentration against F. graminearum [215] |
| 53.10% ar-Turmerone | 3500 and 3000 µg/mL | Complete inhibition of fungal biomass and zearalenone production in F. graminearum, respectively [215] |
| 20.4% α-Phellandrene | 19.8% α-Turmerone | 10.3% 1.8-Cineole | 7.35% β-Turmerone | 0.06–0.36 µg/mL | One of the highest minimum inhibitory concentrations with respect to 11 different essential oils against five-food spoilage yeasts [217] |

**Herbicidal Activity**

| Chemical Composition | Concentration | Effect | Ref. |
|----------------------|---------------|--------|------|
| 38.7% ar-Turmerone  | 18.6% β-Turmerone | 14.2% α-Turmerone | 0.125–1 µL/mL | Reduction of the hypocotyl growth of Portulaca oleracea, Lolium multiflorum and Echinochloa crus-galli in 56.55, 40.45 and 39.33%, respectively, without affecting neither seed germination nor hypocotyl growth of tomato, cucumber and rice crops [234] |
| 38.7% ar-Turmerone  | 18.6% β-Turmerone | 14.2% α-Turmerone | 1 µL/mL | Significant inhibition of Cortaderia selloana seed germination (81.71%) [234] |
| 38.7% ar-Turmerone  | 18.6% β-Turmerone | 14.2% α-Turmerone | >0.125 µL/mL | Outstanding inhibitory effect in the development of C. selloana and Nicotiana glauca [234] |
### Table 3. Cont.

| Chemical Composition | Concentration | Effect                                                                 | Ref. |
|----------------------|---------------|------------------------------------------------------------------------|------|
| **Antimicrobial Activity** |               |                                                                        |      |
| 42.6% α-Turmerone    | IC₅₀ 10.03 mg/mL (DPPH) | Dose-dependent DPPH and ABTS radical scavenging activities, as well as reducing power | [34] |
| 16.0% β-Turmerone    | IC₅₀ 0.54 mg/mL (ABTS) |                                                                        |      |
| 12.9% ar-Turmerone   |               |                                                                        |      |
| **Antioxidant Activity** |               |                                                                        |      |
| 42.6% α-Turmerone    | IC₅₀ 14.5 ± 2.9 mg/mL (DPPH) | Low DPPH bleaching potential and ferric-reducing antioxidant power in comparison to Trolox | [105] |
| 16.0% β-Turmerone    | 389.0 ± 12.0 μM |                                                                        |      |
| 12.9% ar-Turmerone   | Ascorbic Acid (AA) eq. |                                                                        |      |
| <100 Meq/kg (peroxide value) | 0.04–0.08 TBA value | The lowest peroxide value with respect to oleoresins, synthetic antioxidants and essential oil from dry rhizomes. |      |
| 0.04–0.08 TBA value | 5–20 μL (DPPH) | More efficient inhibitory effect of malondialdehyde | [164] |
| 5–100 μL (Fe²⁺ chelating effect) | 100–200 Meq/kg (peroxide value) | Higher DPPH radical scavenging, as well as Fe²⁺ chelating abilities than the dry ones (21.4% ar-turmerone, 7.2% α-santalene and 6.6% ar-curcumene) | [164] |
| 21.4% ar-Turmerone    | 28.1 ± 1.45 mmol Trolox/L (PLC) | Higher DPPH radical scavenging activity than BHA and BHT | [164] |
| 19.8% α-Turmerone    | 10.3% 1,8-Cineole | Free radical-scavenging potential twice higher than that of Trolox (~60 vs. 28.2%, respectively) | [217] |
| 10.3% 1,8-Cineole | 20.4% α-Phellandrene | Antioxidant activity (72.4%) near the values of the reference essential oil Thymus vulgaris (90.9%) and butylated hydroxyanisole (BHA) (86.74%) | [217] |
| 7.35% β-Turmerone    | 7.8% Cumene |                                                                        |      |
| 13.82% ar-Turmerone  | 30 μL/mL | Suppression of oxidase enzyme activity of the fresh-cut “Fuji” apples by 9% when incorporated in a starch/carboxymethyl cellulose edible coating | [261] |
| 22.8% β-Sesquiphellandrene | 3.227 mg/mL (DPPH) | Hydrogen donating properties and reducing power. Potential option to prevent oxidative deterioration of fat containing food products | [256] |
| 9.5% Terpinolene | 1.541 mg/mL (ABTS) |                                                                        |      |
| **Antioxidant Activity** |               |                                                                        |      |
| 35.46% Turmerone    | IC₅₀ 3.227 mg/mL (DPPH) | Dose-dependent DPPH and ABTS radical scavenging activities, as well as reducing power | [34] |
| 20.61% Cumene        | IC₅₀ 1.541 mg/mL (ABTS) |                                                                        |      |
| 13.82% ar-Turmerone  | 1 mg/mL (antiperoxidative) |                                                                        |      |
| 28.7% ar-Turmerone   | 10 μL | Negligible DPPH radical scavenging activity with respect to other different essential oils (cinnamon, clove, green tea, lemon eucalyptus, rosemary, oregano and its main compound carvacrol) | [262] |

On the other hand, other Curcuma spp. essential oil with very different chemical compositions have also demonstrated strong and dose-dependent antioxidant abilities. In this sense, C. zedoaria (17.72% curzerenone, 15.85% γ-eudesmol acetate and 6.50% germacrone) and C. angustifolia (29.62% epicurzerenone, 10.79% curzerenone and 6.12% trans-β-terpineol) rhizome essential oils showed higher DPPH (IC₅₀ 2.58 ± 077 μg/mL and 12.53 ± 0.14 μg/mL) and ABTS (IC₅₀ 1.28 ± 0.05 μg/mL and 5.53 ± 0.29 μg/mL) radical scavenging ability, as well as reducing power (EC₅₀ 4.77 ± 0.14 μg/mL and 5.68 ± 0.11 μg/mL) than BHT and ascorbic acid (DPPH: 19.07 ± 0.17 and 5.31 ± 0.2 μg/mL, ABTS: 14.19 ± 0.21 and 1.51 ± 0.32 μg/mL and reducing power: 9.61 ± 0.18 and 5.21 ± 0.13 μg/mL, respectively) [194]. The leaf essential oil of C. angustifolia (33.2% curz-
erenone, 18.6% 14-hydroxy-δ-cadinene and 7.3% γ-eudesmol acetate) showed even higher DPPH and ABTS free-radical scavenging (4.06 ± 0.06 and 1.35 ± 0.14 µg/mL, respectively), as well as reducing (EC₅₀ 2.62 ± 0.25 µg/mL) activities, than the rhizome oil and the standard references [128]; C. amada rhizome oil (40% β-myrcene, 11.78% β-pinene and 10% ar-curcumene) and the essential oil obtained from the pulverized rhizome of C. petiolata (83.99% 2-methyl-5-pentanol) presented moderate antioxidant activity in comparison to the extracts and standard references [133,263].

C. longa rhizome essential oil has also exhibited strong antioxidant potential when combined with other essential oils—for instance, Z. officinale. In this case, the combination of both showed higher DPPH radical scavenging activity (IC₅₀ 3.75 µL/mL vs. 4.28 and 7.19 µL/mL.), as well as stronger β-carotene–linoleic acid bleaching (65.24% vs. 59.88 and 55.82%) than C. longa and Z. officinale oils alone, respectively [235]. This last test has been commonly used to compare the lipid peroxidation inhibitory activity of either individual compounds or mixtures, despite possible scattered results due to different factors like the chemical composition and extracting solvent [264].

Overall, the genus Curcuma and its derived products have been popularly used as food additives to confer special beneficial properties, which include colouring, preservation and healthy effects. Particularly, the biopreservative properties of C. longa rhizome oil can meet the needs of the agri-food industry. Its suitability as a natural alternative to synthetic antioxidants has been broadly corroborated through many in vitro and in vivo tests, obtaining interesting results replacing the reference synthetic antioxidants. So much so that this essential oil is being included in food coatings to keep them much longer. Moreover, further investigation regarding the most appropriate application of C. longa rhizome oil, as well as combinations with other, different essential oils, is being carried out, with the aim of trying to enhance its antioxidant potential and being finally implemented in the sustainable agri-food industry.

5. Conclusions

Consumers demand natural, safer and greener products, as well as sustainable food technologies, from the agri-food industry. However, an equilibrium between meeting consumer expectations and achieving the maximum efficiency in industrial production according to Green Chemistry is required.

The potential applications of numerous plant products in the agri-food industry have been widely investigated. Amongst them, the essential oil extracted from the rhizome of C. longa (species popularly known for its medicinal and culinary benefits) has demonstrated a high antimicrobial potential against a broad spectrum of plagues in crops and food-spoilage microorganisms, as well as significant phytotoxic effects against diverse weeds that are considered truly a threat for agricultural production and ecology. Besides, it has exhibited interesting antioxidant activity that would avoid postharvest decay and extend food shelf-lives.

This versatility is mainly due to the characteristic chemical composition of C. longa rhizome essential oil. Usually, sesquiterpenes constitute the main phytochemical group identified, and turmerones are the most representative components. However, this pattern is subjected to changes depending on countless internal (genetics) and external (geographic location, cultivation conditions, post-harvest processing, etc.) factors. For this reason, predictive models need to be developed to previse the chemical composition of C. longa rhizome essential oil according to the conditions surrounding the plant. In this way, the control of these factors is useful to obtain a high-yield essential oil with the aimed chemical composition, convenient for carrying out a specific activity in the agri-food industry in an optimum way.

Given the nature of these products (complex mixtures of volatile compounds), one of the first processes to take into account is the extraction technique chosen. Despite that the conventional methods (steam distillation, hydrodistillation, etc.) are still the most commonly used, there is a current tendency to employ the novel ones (SFE, SWE, SFME,
MAE, etc.) that offer several advantages, such as the reduction of costs, of extraction times, energy consumption, etc., in an attempt to offer higher-quality *C. longa* rhizome essential oil in the lowest time possible and with the minimum residues produced. For its total implementation, further research is needed to achieve the most efficient extraction that allows obtaining a chemical composition enriched in the active component to elucidate its mechanisms of action, encapsulating techniques of *C. longa* essential oil for its preservation and/or release against external conditions (temperature, oxygen, etc.), as well as to determine the threshold application with which it would neither damage crops nor affect the organoleptic properties of food products, are necessary research prior to their employment in the agri-food industry.

The sustainable and efficient encapsulation of *C. longa* rhizome oil represents the ultimate step for its implementation in the agri-food industry. Current research is oriented to solve the limitations when applying turmeric essential oil (volatility, instability under certain conditions and hydrophobicity), with the aim of longer preserving its numerous benefits and improving its performance. Biodegradable and biocompatible products as edible alginate-based films with turmeric represent advantages over traditional plastic containers, increasing the antioxidant capacity and extending the shelf-lives of the final products. Many encapsulation methods, including β-cyclodextrines, chitosan–alginate, microemulsions, nanoparticles etc., have been described to enhance the curcumin bioavailability. They represent potential options to also enhance the beneficial properties of the essential oil of *C. longa* rhizome and its components, as well as controlling their release. A complex study regarding the cost-efficiency and sustainability, as well as threshold concentrations not to harm crops and food, have to be taken into account.

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**References**

1. Singab, A.N.B.I. Medicinal & Aromatic Plants. *Med. Aromat. Plants* 2012, 1, 1000e109.
2. Inoue, M.; Hayashi, S.; Craker, L.E. Role of medicinal and aromatic plants: Past, present, and future. In *Pharmacognosy-Medicinal Plants*; Perveen, S., Al-Taweel, A., Eds.; IntechOpen: London, UK, 2019; pp. 13–26. [CrossRef]
3. Saiz de Cos, P. *Cúrcuma I (Curcuma longa L.). Reducia Ser. Botánica* 2014, 7, 84–99.
4. Araújo, C.A.C.; Leon, L.L. Biological activities of *Curcuma longa L.*. *Memórias Inst. Oswaldo Cruz* 2001, 96, 723–728. [CrossRef] [PubMed]
5. Luthra, P.M.; Singh, R.; Chandra, R. Therapeutic uses of *Curcuma longa* (turmeric). *Indian J. Clin. Biochem.* 2001, 16, 153–160. [CrossRef] [PubMed]
6. Wickenberg, J.; Ingemansson, S.L.; Hlebowicz, J. Effects of *Curcuma longa* (turmeric) on postprandial plasma glucose and insulin in healthy subjects. *Nutr. J.* 2010, 9, 43. [CrossRef]
7. Vaughan, A.R.; Branum, A.; Sivamani, R.K. Effects of turmeric (*Curcuma longa*) on skin health: A systematic review of the clinical evidence. *Phytother. Res.* 2016, 30, 1243–1264. [CrossRef]
8. Dasgupta, A. Antiinflammatory herbal supplements. In *Translational Inflammation*; Actor, J.K., Smith, K.C., Eds.; Elsevier Inc.: London, UK, 2019; pp. 69–91. [CrossRef]
9. El-Kenawy, A.E.-M.; Hassan, S.M.A.; Mohamed, A.M.M.; Mohammed, H.M.A.M. Tumeric or *Curcuma longa* Linn. In *Nonvitamin and Nonmineral Nutritional Supplements*; Nabavi, S.M., Sanches Silva, A., Eds.; Elsevier Inc.: London, UK, 2019; pp. 447–453. [CrossRef]
10. Ortega, A.M.M.; Segura Campos, M.R. Medicinal plants and their bioactive metabolites in cancer prevention and treatment. In *Bioactive Compounds: Health Benefits and Potential Applications*; Campos, M.R.S., Ed.; Elsevier Inc.: Duxford, UK, 2019; pp. 83–109. [CrossRef]
11. Rajagopal, K.; Varakumar, P.; Baliwada, A.; Byran, G. Activity of phytochemical constituents of Curcuma longa (turmeric) and Andrographis paniculata against coronavirus (COVID-19): An in silico approach. *Future J. Pharm. Sci.* 2020, 6, 104. [CrossRef]

12. Alvis, A.; Arrazola, G.; Martinez, W. Evaluation of antioxidant activity and potential hydro-alcoholic extracts of curcuma (*Curcuma longa*). *Inf. Tecnol.* 2012, 23, 11–18. [CrossRef]

13. Sawant, R.S.; Godghate, A.G. Qualitative phytochemical screening of rhizomes of *Curcuma longa* Linn. *Int. J. Sci. Environ. Technol.* 2013, 2, 634–641.

14. Abraham, A.; Samuel, S.; Mathew, L. Pharmacognostic evaluation of *Curcuma longa* L. rhizome and standardization of its formulation by HPLC using curcumin as marker. *Int. J. Pharmcogn. Phytochem. Res.* 2018, 10, 38–42.

15. Meng, F.; Zhou, Y.; Ren, D.; Wang, R. Turmeric: A review of its chemical composition, quality control, bioactivity, and pharmaceutical application. In *Natural and Artificial Flavoring Agents and Food Dyes*; Grumezescu, A.M., Holban, A.M., Eds.; Elsevier Inc.: London, UK, 2018; pp. 299–350. [CrossRef]

16. Carballido, E. Características de la Planta de la Curcuma. Available online: https://www.botanical-online.com/plantas-medicinales/curlcuma-caracteristicas (accessed on 18 November 2020).

17. Li, S.; Yuan, W.; Deng, G.; Wang, P.; Aggarwal, B.B. Chemical composition and product quality control of turmeric (*Curcuma longa* L.). *Pharm. Crops* 2011, 2, 28–54. [CrossRef]

18. González-Albadalejo, J.; Sanz, D.; Claramunt, R.M.; Lavandera, J.L.; Alkorta, I.; Elguero, J. Curcumin and curcuminoids: Chemistry, structural studies and biological properties. *An. Real Acad. Nat. Farm.* 2015, 81, 278–310.

19. Ramesh, T.N.; Paul, M.; Manikanta, K.; Girish, K.S. Structure and morphological studies of curcuminoids and curcuminoid mixture. *J. Cryst. Growth* 2020, 547, 125811. [CrossRef]

20. Bambirra, M.L.A.; Junqueira, R.G.; Glória, M.B. Influence of post harvest processing conditions on yield and quality of ground turmeric (*Curcuma longa* Linn.). *Bras. Arch. Biol. Technol.* 2002, 45, 423–429. [CrossRef]

21. Amalraj, A.; Pius, A.; Gopi, S. Biological activities of curcuminoids, other biomolecules from turmeric and their derivatives—A review. *J. Tradit. Chin. Med. Sci.* 2017, 7, 205–233. [CrossRef][PubMed]

22. Bengmark, S.; Mesa, M.D.; Gil, A. Plant-derived health: The effects of turmeric and curcuminoids. *Nutr. Hosp.* 2009, 24, 273–281. [PubMed]

23. Tayyem, R.F.; Heath, D.D.; Al-delaimy, W.K.; Rock, C.L.; Tayyem, R.F.; Heath, D.D.; et al. Curcumin content of turmeric (*Curcuma longa* L.). *Pharm. Crops* 2011, 2, 28–54. [CrossRef]

24. Siviero, A.; Gallo, E.; Maggini, V.; Gori, L.; Mugelli, A.; Firenzuoli, F.; Vannacci, A. Curcumin, a golden spice with a low bioavailability. *J. Herb. Med.* 2015, 5, 57–70. [CrossRef]

25. Akbar, A.; Kuanar, A.; Joshi, R.K.; Sandeep, I.S.; Mohanty, S. Development of prediction model and experimental validation in predicting the curcumin content of turmeric (*Curcuma longa*). *Front. Plant Sci.* 2016, 7, 1507. [CrossRef]

26. Tung, B.T.; Nham, D.T.; Hai, N.T.; Thu, D.K. *Curcuma longa*, the polyphenolic curcumin compound and pharmacological effects on liver. In *Dietary Interventions in Liver Disease*; Watson, R.R.; Preedy, V.R., Eds.; Elsevier Inc.: London, UK, 2019; pp. 125–134. [CrossRef]

27. Soleiman, V.; Sahebkar, A.; Hosseinzadeh, H. Turmeric (Curcuma longa) and its major constituent (curcumin) as nontoxic and safe substances: Review. *Phytother. Res.* 2018, 32, 985–995. [CrossRef]

28. Changtam, C.; De Koning, H.P.; Ibrahim, H.; Sajid, M.S.; Gould, M.K.; Suksamrarn, A. Curcuminoid analogs with potent activity against *Trypanosoma* and *Leishmania* species. *Eur. J. Med. Chem.* 2010, 45, 941–956. [CrossRef][PubMed]

29. Priyadarssini, K.I. Chemical and structural features influencing the biological activity of curcumin. *Curr. Pharm. Des.* 2013, 19, 2093–2100. [PubMed]

30. Arshad, L.; Nasir, S.; Bukhari, A.; Jantan, I. An overview of structure-activity relationship studies of curcumin analogs as antioxidant and anti-inflammatory agents. *Future Med. Chem.* 2017, 9, 605–626. [CrossRef][PubMed]

31. Nouroreddin, S.A.; El-shisthawy, R.M.; Al-footy, K.O. Curcumin analogues and their hybrid molecules as multifunctional drugs. *Eur. J. Med. Chem.* 2019, 182, 111631. [CrossRef][PubMed]

32. Benzaria, A.; Maresca, M.; Taieb, N.; Dumay, E. Interaction of curcumin with phosphocasein micelles processed or not by dynamic high-pressure. *Food Chem.* 2013, 138, 2327–2337. [CrossRef]

33. Devkota, L.; Rajbhandari, M. Composition of essential oils in turmeric rhizome. *Nepal J. Sci. Technol.* 2015, 16, 87–94. [CrossRef]

34. Avanco, G.B.; Ferreira, F.D.; Bomfim, N.S.; Santos, P.A.D.S.R.D.; Peralta, R.M.; Brugnari, T.; Mallmann, C.A.; de Filho, B.A.A.; Mikcha, J.M.G.; Machinski, M., Jr. *Curcuma longa* L. essential oil composition, antioxidant effect, and effect on *Fusarium verticillioides* and fumonisin production. *Food Control* 2017, 73, 806–813. [CrossRef]

35. Ferreira Guimaraes, A.; Andrade Vinhas, A.C.; Ferraz Gomes, A.; Souza, L.H.; Baier Krepsky, P. Essential oil of *Curcuma longa* L. rhizomes chemical composition, yield variation and stability. *Quim. Nova* 2020, 43, 909–913. [CrossRef][PubMed]

36. Babu, G.D.K.; Shameemagum, V.; Ravindranath, S.D.; Joshi, V.P. Comparison of chemical composition and antifungal activity of *Curcuma longa* L. leaf oils produced by different water distillation techniques. *Flavour Fragn.* J. 2007, 22, 191–196. [CrossRef]

37. Usman, L.A.; Hamid, A.A.; George, O.C.; Ameen, O.M.; Muhammad, N.O.; Zubair, M.F.; Lawal, A. Chemical composition of rhizome essential oil of *Curcuma longa* L. growing in North Central Nigeria. *World J. Chem.* 2009, 4, 178–181.

38. Niranjana, A.; Singh, S.; Dhiman, M.; Tewari, S.K. Biochemical composition of *Curcuma longa* L. accessions. *Anal. Lett.* 2013, 46, 1069–1083. [CrossRef]
39. Akbar, A.; Kuanar, A.; Sandeep, I.S.; Kar, B.; Singh, S.; Mohanty, S.; Patnaik, J.; Nayak, S. GC-MS analysis of essential oil of some high drug yielding genotypes of turmeric (Curcuma longa L.). Int. J. Pharm. Pharm. Sci. 2015, 7, 35–40.
40. Sandeep, I.S.; Das, S.; Nayak, S.; Mohanty, S. Chemometrical profile of Curcuma longa L. towards standardization of factors for high essential oil yield and quality. Proc. Natl. Acad. Sci. India Sect. B Biol. Sci. 2018, 88, 949–957. [CrossRef]
41. Choudhary, V.K.; Kumar, P.S. Weed suppression, nutrient leaching, water use and yield of turmeric (Curcuma longa L.) under different land configurations and mulches. J. Clean. Prod. 2019, 210, 795–803. [CrossRef]
42. Leela, N.K.; Tava, A.; Shafi, P.M.; Sinu, P.J.; Chempakam, B. Chemical composition of essential oils of turmeric. Acta Pharm. 2002, 52, 137–141.
43. Raina, V.K.; Srivastava, S.K.; Syamsundar, K.V. Rhizome and leaf oil composition of Curcuma longa from the lower himalayan region of northern India. J. Essent. Oil Res. 2005, 17, 556–559. [CrossRef]
44. Awasthi, P.; Dixit, S. Chemical composition of Curcuma longa leaves and rhizome oil from the plains of Northern India. J. Young Pharm. 2009, 1, 312–319. [CrossRef]
45. Singh, S.; Panda, M.K.; Subudhi, E.; Nayak, S. Chemical composition of leaf and rhizome oil of an elite genotype Curcuma longa L. from South Eastern ghats of Orissa. J. Pharm. Res. 2013, 6, 1630–1633.
46. Mishra, R.; Gupta, A.K.; Kumar, A.; Lal, R.K.; Saikia, D.; Chanotiya, C.S. Genetic diversity, essential oil composition, and in vitro antioxidant and antimicrobial activity of Curcuma longa L. germplasm collections. J. Appl. Res. Med. Aromat. Plants 2018, 10, 75–84. [CrossRef]
47. Dosoky, N.S.; Setzer, W.N. Chemical composition and biological activities of essential oils of Curcuma species. Nutrients 2018, 10, 1196. [CrossRef]
48. Kim, D.; Suh, Y.; Lee, H.; Lee, Y. Immune activation and antitumor response of ar-turmerone on P388D1 lymphoblast cell implanted tumors. Int. J. Mol. Med. 2013, 31, 386–392. [CrossRef] [PubMed]
49. Nair, A.; Amalraj, A.; Jacob, J.; Kunnumakkara, A.B.; Gopi, S. Non-curcuminoids from turmeric and their potential in cancer therapy and anticancer drug delivery formulations. Biomolecules 2019, 9, 13. [CrossRef] [PubMed]
50. Jankasem, M.; Wuthi-udomlert, M.; Gritsanapan, W. Antidermatophytic properties of ar-turmerone, turmeric oil, and Curcuma longa preparations. ISRN Dermatol. 2013, 2013, 250597. [CrossRef] [PubMed]
51. Yue, G.G.L.; Kwok, H.F.; Lee, J.K.M.; Jiang, L.; Chan, K.M.; Cheng, L.; Leung, P.C.; Fung, K.P.; Lau, C.B.S. Novel anti-angiogenic effects of aromatic-turmerone, essential oil isolated from spice turmeric. J. Funct. Foods 2015, 15, 243–253. [CrossRef]
52. Orellana-paucar, A.M.; Afrikanova, T.; Aibuldinov, Y.K.; Dehaen, W.; De Witte, P.A.M.; Esguerra, C.V. Insights from Eucalyptus globulus L. germplasm collections. J. Clean. Prod. 2018, 201, 210–218. [CrossRef]
53. Hucklenbroich, J.; Klein, R.; Neumaier, B.; Graf, R.; Fink, G.R.; Schroeter, M.; Rueger, M.A. Aromatic-turmerone induces neural stem cell proliferation in vitro and in vivo. Stem Cell Res. Ther. 2014, 5, 100. [CrossRef]
54. Li, Y.; Du, Z.; Li, P.; Yan, L.; Zhou, W.; Tang, Y. Aromatic-turmerone ameliorates imiquimod-induced psoriasis-like inflammation of BALB/c mice. Int. Immunopharmacol. 2016, 42, 319–325. [CrossRef]
55. Khayreddine, B. Essential Oils, An Alternative to Synthetic Food Additives and Thermal Treatments; MedCrave Group LLC: Edmond, OK, USA, 2018; pp. 1–44.
56. Boskovic, M.; Baltic, Z.M.; Ivanovic, J.; Duric, J.; Loncina, J.; Dokmanovic, M.; Markovic, R. Use of essential oils in order to prevent foodborne illnesses caused by pathogens in meat. Tehnol. Mesa 2013, 54, 14–20. [CrossRef]
57. Mihai, A.L.; Popa, M.E. Essential oils utilization in food industry—A literature review. Sci. Bull. Ser. F Biotechnol. 2013, 37, 187–192.
58. Mihai, A.L.; Popa, M.E. Inhibitory effects of essential oils with potential to be used in food industry. Sci. Pharm. 2014, 18, 220–225.
59. Bhavaniramya, S.; Vishnupriya, S.; Al-aboody, M.S. Role of essential oils in food safety: Antimicrobial and antioxidant applications. Grain Oil Sci. Technol. 2019, 2, 49–55. [CrossRef]
60. Boukhatem, M.N.; Boumaiza, A.; Nada, H.G.; Rajabi, M. Eucalyptus globulus essential oil as a natural food preservative: Antioxidant, antibacterial and antifungal properties in vitro and in a real food matrix (orangina fruit juice). Appl. Sci. 2020, 10, 5581. [CrossRef]
61. Ibáñez, M.D. Commercial Essential Oils: Sustainable Alternatives in the Agri-Food Industry. Ph.D. Thesis, Universitat de València, València, Spain, 2019.
62. Ibáñez, M.D.; Sanchez-Ballester, N.M.; Blázquez, M.A. Encapsulated limonene: A pleasant lemon-like aroma with promising application in the agri-food industry. A review. Molecules 2020, 25, 2598. [CrossRef]
63. Weiss, E.A. Turmeric. In Spice Crops; CABI Publishing: Wallingford, CT, USA, 2002; pp. 338–352.
64. Balakrishan, K. Postharvest technology and processing of turmeric. In Turmeric. The Genus Curcuma; Ravindran, P., Nirman Babu, K., Sivaraman, K., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 193–256.
65. Pereira, C.G.; Meireles, M.A.A. Supercritical fluid extraction of bioactive compounds: Fundamentals, applications and economic perspectives. Food Bioprocess Technol. 2010, 3, 340–372. [CrossRef]
66. Sorensen, E. Principles of Binary Distillation. In Distillation: Fundamentals and Principles; Górák, A., Sorensen, E., Eds.; Elsevier: Oxford, UK, 2014; pp. 145–186.
67. Akdag, A.; Ozturk, E. Distillation methods of essential oils. Nisan 2019, 45, 22–31.
68. Hielscher Ultrasonic Hydrodistillation of Essential Oils. Available online: https://www.hielscher.com/ultrasonic-hydrodistillation-of-essential-oils.htm (accessed on 5 July 2020).

69. Gujarathi, D.B.; Ilay, N.T. Continuous water circulation distillation: A modification of steam distillation. J. Chem. Educ. 1993, 70, 86. [CrossRef]

70. Santos, D.T.; Angela, A.; Meireles, M. Extraction of volatile oils by supercritical fluid extraction: Patent survey. Recent Patents Eng. 2011, 5, 17–22. [CrossRef]

71. Chandra, A.; Rajapati, S.; Garg, S.K.; Rathore, A.K. Extraction of turmeric oil by continuous water circulation distillation. Int. J. Sci. Eng. Appl. Sci. 2016, 2, 2395–3470.

72. Matsumura, S.; Murata, K.; Zaima, N.; Yoshioka, Y.; Morimoto, M.; Kugo, H.; Yamamoto, A.; Moriyama, T.; Matsuda, H. Inhibitory activities of essential oil obtained from turmeric and its constituents against β-secretase. Nat. Prod. Commun. 2016, 11, 1785–1788. [CrossRef]

73. Sehgal, H.; Jain, T.; Malik, N.; Chandra, A.; Singh, S. Isolation and chemical analysis of turmeric oil from rhizomes. In Proceedings of the Chemical Engineering Towards Sustainable Development, Chennai, India, 27–30 December 2016; pp. 1–14.

74. Masango, P. Cleaner production of essential oils by steam distillation. J. Clean. Prod. 2005, 13, 833–839. [CrossRef]

75. De Oliveira, M.S.; Silva, S.G.; da Cruz, J.N.; Ortiz, E.; da Costa, W.A.; Bezerra, F.W.F.; Cunha, V.M.B.; Cordeiro, R.M.; Al, E. Supercritical CO₂ application in essential oil extraction. In Industrial Applications of Green Solvents: Volume II; Inamuddin, D., Mobin, R., Asiri, A.M., Eds.; Materials Research Forum LLC: Millersville, PA, USA, 2019; pp. 1–28.

76. Silva, L.V.; Nelson, D.L.; Drummond, M.F.B.; Dufossé, L.; Glória, M.B.A. Comparison of hydrodistillation methods for the deodorization of turmeric. Food Res. Int. 2005, 38, 1087–1096. [CrossRef]

77. Gupta, A.; Naranival, M.; Kothari, V. Modern extraction methods for preparation of bioactive plant extracts. Int. J. Appl. Nat. Sci. 2012, 1, 8–26.

78. Tran, T.H.; Nguyen, P.T.N.; Pham, T.N.; Nguyen, D.C.; Dao, T.P.; Nguyen, T.D.; Nguyen, D.H.; Vo, D.V.N.; Le, X.T.; Le, N.T.H.; and et al. Green technology to optimize the extraction process of turmeric (Curcuma longa L.) oils. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Sanya, China, Sanya, China, 17–19 November, 2018; IOP Publishing Ltd.: Bristol, UK, 2019; Volume 479, pp. 1–6. [CrossRef]

79. Haiyee, Z.A.; Shah, S.H.M.; Ismail, K.; Hashim, N.; Ismail, W.I.W. Quality parameters of Curcuma longa L. extracts by supercritical fluid extraction (SFE) and ultrasonic assisted extraction (UAE). Malays. J. Anal. Sci. 2016, 20, 626–632. [CrossRef]

80. Sahne, F.; Mohammadi, M.; Najafpour, G.D.; Moghadamnia, A.A. Extraction of bioactive compound curcumin from turmeric (Curcuma longa L.) via different routes: A comparative study. Pak. J. Biotechnol. 2016, 13, 173–180.

81. Lee, W.-J.; Suleiman, N.; Hadzir, N.H.N.; Chong, G.-H. Supercritical fluids for the extraction of oleoresins and plant phenolics. In Green Sustainable Process for Chemical and Environmental Engineering and Science; Inamuddin, D., Asiri, A.M., Isloor, A.M., Eds.; Elsevier Inc.: Cambridge, MA, USA, 2020; pp. 425–451. [CrossRef]

82. Capuzzo, A.; Maffei, M.E.; Occhipinti, A. Supercritical fluid extraction of plant flavors and fragrances. Molecules 2013, 18, 7194–7238. [CrossRef] [PubMed]

83. Wrona, O.; Rafańska, K.; Możeński, C.; Buszewski, B. Supercritical fluid extraction of bioactive compounds from plant materials. J. AOAC Int. 2017, 100, 1624–1635. [CrossRef] [PubMed]

84. Yousefi, M.; Rahimi-Nasrabadi, M.; Pourmortazavi, S.M.; Wysokowski, M.; Jesionowski, T.; Ehrlich, H.; Mirsadeghi, S. Supercritical fluid extraction of essential oils. TrAC Trends Anal. Chem. 2019, 118, 182–193. [CrossRef]

85. Mottahedeh, P.; Asl, A.H.; Khaenooori, M. Extraction of curcumin and essential oil from Curcuma longa L. by subcritical water via response surface methodology. J. Food Process. Preserv. 2017, 41. [CrossRef]

86. Khanam, S. Influence of operating parameters on supercritical fluid extraction of essential oil from turmeric root. J. Clean. Prod. 2018, 188, 816–824. [CrossRef]

87. Chang, L.H.; Jong, T.T.; Huang, H.S.; Nien, Y.F.; Chang, C.M.J. Supercritical carbon dioxide extraction of turmeric oil from Curcuma longa Linn and purification of turmeric oil. Sep. Purif. Technol. 2006, 47, 119–125. [CrossRef]

88. Khezeli, T.; Ghaedi, M.; Bahrani, S.; Daneshfar, A. Supercritical fluid extraction in separation and preconcentration of organic and inorganic species. In New Generation Green Solvents for Separation and Preconcentration of Organic and Inorganic Species; Soyolak, M., Yilmaz, E., Eds.; Elsevier Inc.: Cambridge, MA, USA, 2020; pp. 425–451. [CrossRef]

89. Khezeli, T.; Ghaedi, M.; Bahrani, S.; Daneshfar, A. Supercritical fluid extraction in separation and preconcentration of organic and inorganic species. In New Generation Green Solvents for Separation and Preconcentration of Organic and Inorganic Species; Soyolak, M., Yilmaz, E., Eds.; Elsevier Inc.: Cambridge, MA, USA, 2020; pp. 425–451. [CrossRef]

90. Chang, L.H.; Jong, T.T.; Huang, H.S.; Nien, Y.F.; Chang, C.M.J. Supercritical carbon dioxide extraction of turmeric oil from Curcuma longa Linn and purification of turmeric oil. Sep. Purif. Technol. 2006, 47, 119–125. [CrossRef]

91. Carvalho, P.I.N.; Osorio-Tobón, J.F.; Rostagno, M.A.; Mauricio, A.; Petenate, A.J.; Meireles, A.A. Optimization of the ar-turmerone extraction from turmeric (Curcuma longa L.) using supercritical carbon dioxide. In Proceedings of the 14th European Meeting on Supercritical Fluids, Marsella, France, 18–21 May 2014.

92. Carvalho, P.I.N.; Osorio-Tobón, J.F.; Rostagno, M.A.; Petenate, A.J.; Meireles, A.A. Techno-economic evaluation of the extraction of turmeric (Curcuma longa L.) oil and ar-turmerone using supercritical carbon dioxide. J. Supercrit. Fluids 2015, 105, 44–54. [CrossRef]

93. Topiar, M.; Sajfrtova, M.; Karban, J.; Sovova, H. Fractionation of turmerones from turmeric SFE isolate using semi-preparative supercritical chromatography technique. J. Ind. Eng. Chem. 2019, 77, 223–229. [CrossRef]

94. Essien, S.O.; Young, B.; Baroutian, S. Recent advances in subcritical water and supercritical carbon dioxide extraction of bioactive compounds from plant materials. Trends Food Sci. Technol. 2020, 97, 156–169. [CrossRef]
Plants 2021, 10, 44

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94. Gbashi, S.; Adebo, O.A.; Piater, L.; Madala, N.E.; Njobeh, P.B. Subcritical water extraction of biological materials. Sep. Purif. Rev. 2017, 46, 21–34. [CrossRef]

95. Baysal, T.; Demirdoven, A. Ultrasound in food technology. In Handbook on Applications of Ultrasound: Sonochemistry for Sustainability; Chen, D., Sharma, S.K., Mudhoo, A., Eds.; CRC Press: Boca Raton, FL, USA, 2011; pp. 163–182.

96. Cardoso-Ugarte, G.A.; Juarez-Becerra, G.P.; Sosa-Morales, M.E.; Lopez-Malo, A. Microwave-assisted extraction of essential oils from herbs. J. Microv. Power Electromagn. Energy 2013, 47, 63–72. [CrossRef]

97. Aziz, N.A.A.; Hassan, J.; Osman, N.H.; Abbas, Z. Extraction of essential oils from Zingiberaceae family by using solvent-free microwave extraction (SFME), microwave-assisted extraction (MAE) and hydrodistillation (HD). Asian J. Appl. Sci. 2017, 5, 97–100.

98. Akloul, R.; Benkaci-Ali, F.; Eppe, G. Kinetic study of volatile oil of Curcuma longa L. rhizome and Curum carvi L. fruits extracted by microwave-assisted techniques using the cryogrinding. J. Essent. Oil Res. 2014, 26, 473–485. [CrossRef]

99. Ching, W.-Y.; Bin-Yusoff, Y.; Wan-Amarina, W.-N.B. Extraction of essential oil from Herba Curcumae. J. Funct. Foods 2013, 5, 620–624. [CrossRef] [PubMed]

100. Hafizuddin Mokhtar, M. Extraction of Essential Oil from Turmeric (Curcuma longa). Bachelor’s Thesis, Universiti Teknologi MARA, Selangor, Malaysia, 2017.

101. Zhilyakova, E.; Novikov, O.; Pisarev, D.; Boyko, N.; Nikitin, K. Prospects of using freons as extractants of Curcuma longa L. root essential oil. Adv. Biol. Sci. Res. 2019, 7, 373–376. [CrossRef]

102. Shang, Z.-P.; Xu, L.-L.; Lu, Y.-Y.; Guan, M.; Li, D.-Y.; Bai, Z.-L.; Qiao, X.; Ye, M. Advances in chemical constituents and quality control of turmeric. World J. Tradit. Chin. Med. 2014, 5, 116–121. [CrossRef]

103. Prabhakaran Nair, K. Antimicrobial properties of turmeric (Curcuma longa L.) rhizome-derived ar-turmerone and curcumin. BioFactors 2013, 39, 237–246. [CrossRef]

104. Manzan, A.C.C.M.; Toniolo, F.S.; Bredow, E.; Povh, N.P. Extraction of essential oil and pigments from Curcuma longa L. by steam distillation and extraction with volatile solvents. J. Agric. Food Chem. 2003, 51, 6802–6807. [CrossRef] [PubMed]

105. Afzal, A.; Oriqat, G.; Khan, M.A.; Jose, J.; Afzal, M. Chemistry and biochemistry of terpenoids from Zingiberaceae family. World J. Tradit. Chin. Med. 2017, 7, 1–10. [CrossRef]

106. Del Prete, D.; Millaro, F.; Chianese, G.; Collado, J.A.; Munoz, E.; Appendino, G.; Taglialatela-Scafati, O. Turmeric sesquiterpenoids: Expeditious resolution, comparative bioactivity, and a new bicyclic turmeronoid. J. Nat. Prod. 2016, 79, 267–273. [CrossRef] [PubMed]

107. Coy Barrera, C.C.A.; Eunice Acosta, G. Antibacterial activity and chemical composition of essential oils of rosemary (Rosmarinus officinalis), thyme (Thymus vulgaris) and turmeric (Curcuma longa) from Colombia. Rev. Cuba. Plantas Med. 2013, 18, 237–246. [CrossRef]

108. Jain, V.; Prasad, V.; Singh, S.; Pal, R. HPTLC method for the quantitative determination of ar-turmerone and Turmerone in lipid soluble fraction from Curcuma longa. Nat. Prod. Commun. 2007, 2, 927–932. [CrossRef]

109. Prabhakaran Nair, K. Turmeric (Curcuma longa L.) and ginger (Zingiber officinale Rosc.)—World’s Invaluable Medicinal Spices the Agronomy and Economy of Turmeric: Springer: Cham, Switzerland, 2019; pp. 1–568.

110. Murakami, A.; Furukawa, I.; Miyamoto, S.; Tanaka, T.; Ohgishi, H. Curcumin combined with turmerones, essential oil components of turmeric, abolishes inflammation-associated mouse colon carcinogenesis. BioFactors 2013, 39, 221–232. [CrossRef] [PubMed]

111. Yue, G.G.L.; Cheng, S.W.; Yu, H.; Xu, Z.S.; Lee, J.K.M.; Hon, P.M.; Lee, M.Y.H.; Kennelly, E.J.; Deng, G.; Yeung, S.K.; et al. The role of turmerones on curcumin transportation and P-glycoprotein activities in intestinal caco-2 cells. J. Med. Food 2012, 15, 242–252. [CrossRef] [PubMed]

112. Yue, G.G.L.; Jiang, L.; Kwok, H.F.; Lee, J.K.M.; Chan, K.M.; Fung, K.P.; Leung, P.C.; Lau, C.B.S. Turmeric ethanolic extract possesses stronger inhibitory activities on colon tumour growth than curcumin—The importance of turmerones. J. Funct. Foods 2016, 22, 565–577. [CrossRef]

113. Lee, H.S. Antimicrobial properties of turmeric (Curcuma longa L.) rhizome-derived ar-turmerone and curcumin. Food Sci. Biotechnol. 2006, 15, 559–563. [CrossRef] [PubMed]

114. Baik, K.U.; Jung, S.H.; Ahn, B.Z. Recognition of pharmacophore of ar-turmerone for its anticancer activity. Arch. Pharm. Res. 1993, 16, 254–256. [CrossRef]
120. Arataneechume, Y.; Komiya, T.; Moteki, H.; Katsuzaki, H.; Imai, K.; Hibasami, H. Selective induction of apoptosis by ar-turmerone isolated from turmeric (*Curcuma longa*) in two human leukemia cell lines, but not in human stomach cancer cell line. *Int. J. Mol. Med.* **2002**, *9*, 481–484. [CrossRef]

121. Cheng, S.B.; Wu, L.C.; Hsieh, Y.C.; Wu, C.H.; Chan, Y.J.; Chang, L.H.; Chang, C.M.; Hsu, S.L.; Teng, C.L.; Wu, C.C. Supercritical carbon dioxide extraction of aromatic turmerone from *Curcuma longa* Linn. Induces apoptosis through reactive oxygen-species-triggered intrinsic and extrinsic pathways in human hepatocellular carcinoma HepG2 cells. *J. Agric. Food Chem.* **2012**, *60*, 9620–9630. [CrossRef]

122. Chen, M.; Chang, Y.Y.; Huang, S.; Xiao, L.H.; Zhou, W.; Zhang, L.Y.; Li, C.; Zhou, R.P.; Tang, J.; Lin, L.; et al. Aromatic-turmerone attenuates LPS-induced neuroinflammation and consequent memory impairment by targeting TLR4-dependent signaling pathway. *Mol. Nutr. Food Res.* **2018**, *62*, 1700281. [CrossRef]

123. Yang, S.; Liu, J.; Jiao, J.; Jiao, L. Ar-turmerone exerts anti-proliferative and anti-inflammatory activities in HaCaT keratinocytes by inactivating hedgehog pathway. *Inflammation* **2020**, *43*, 478–486. [CrossRef] [PubMed]

124. Zhang, L.; Yang, Z.; Wei, J.; Su, P.; Chen, D.; Pan, W.; Zhou, W.; Zhang, K.; Zheng, X.; Lin, L.; et al. Contrastive analysis of chemical composition of essential oil from twelve *Curcuma* species distributed in China. *Ind. Crops Prod.* **2017**, *108*, 17–25. [CrossRef]

125. Devi, L.R.; Rana, V.S.; Devi, S.I.; Blázquez, M.A.; Devi, L.R.; Rana, V.S.; Devi, S.I. Chemical composition and antimicrobial activity of the essential oil of *Curcuma leucorrhiza* Roxb. *J. Essent. Oil Res.* **2012**, *24*, 533–538. [CrossRef]

126. Jantan, I.; Saputri, F.C.; Qaisar, M.N.; Buang, F. Correlation between chemical composition of *Curcuma domestica* and *Curcuma xanthorrhiza* and their antioxidant effect on human low-density lipoprotein oxidation. *Evidence-Based Complement. Altern. Med.* **2012**, *2012*, 523–526. [CrossRef] [PubMed]

127. Singh, P.; Singh, S.; Kapoor, I.P.S.; Singh, G.; Isidorov, V.; Szczepaniak, L. Chemical composition and antioxidant activities of essential oil and oleoresins of *Curcuma zedoaria* rhizomes, part-74. *Food Biosci.* **2013**, *3*, 42–48. [CrossRef]

128. Jena, S.; Ray, A.; Banerjee, A.; Sahoo, A.; Nasim, N.; Sahoo, S.; Kar, B.; Patnaik, J.; Panda, P.C.; Nayak, S. Chemical composition and antioxidant activity of essential oil from leaves and rhizomes of *Curcuma angustifolia* Roxb. *Nat. Prod. Res.* **2017**, *31*, 2188–2191. [CrossRef]

129. Zhu, J.; Lower-Nedza, A.D.; Hong, M.; Jiec, S.; Wang, Z.; Yingmao, D.; Jantan, I.; Saputri, F.C.; Qaisar, M.N.; Buang, F. Correlation between chemical composition of *Curcuma domestica* and *Curcuma xanthorrhiza* and their antioxidant effect on human low-density lipoprotein oxidation. *Evidence-Based Complement. Altern. Med.* **2012**, *2012*, 523–526. [CrossRef] [PubMed]

130. Hong, S.L.; Lee, G.S.; Rahman, S.N.S.A.; Hamdi, O.A.A.; Awang, K.; Nugroho, N.A.; Malek, S.N.A. Essential oil content of the rhizome of *Curcuma purpurascens* Bl. (Temu Tis) and its antiproliferative effect on selected human carcinoma cell lines. *Sci. World J.* **2014**, *2014*, 397430. [CrossRef]

131. König, W.A.; Rieck, A.; Hardt, I.; Gehrcke, B.; Kubeczka, K.-H.; Muhle, H. Enantiomeric composition of the chiral constituents of essential oils. Part 2: Sesquiterpene hydrocarbons. *J. High Resolut. Chromatogr.* **1994**, *17*, 315–320. [CrossRef]

132. Chizzola, R. Regular monoterpenes and sesquiterpenes. In *Natural Products: Phytochemistry, Botany and Metabolism of Alkaloids, Phenolics and Terpenes*; Ramawat, K.G., Mériton, J.M., Eds.; Springer: Heidelberg, Germany, 2013; pp. 2973–3008. [CrossRef]

133. Tamta, A.; Prakash, O.; Punetha, H.; Pant, A.K. Chemical composition and *in vitro* antioxidant potential of essential oil and rhizome extracts of *Curcuma amada* Roxb. *Cogent Chem.* **2016**, *2*, 1–11. [CrossRef]

134. Chane-Ming, J.; Vera, R.; Chalchat, J.C.; Cabassu, P. Chemical composition of essential oil from rhizomes, leaves and flowers of *Curcuma longa* L. from Reunion Island. *J. Essent. Oil Res.* **2006**, *18*, 429–425. [CrossRef]

135. Garg, S.N.; Mengi, N.; Patra, N.K.; Charles, R.; Kumar, S. Chemical examination of the leaf essential oil of *Curcuma longa* L. from the North Indian plains. *Flavour Fragr. J.* **2002**, *17*, 103–104. [CrossRef]

136. Pande, C.; Chanoitiya, C.S. Constituents of the leaf oil of *Curcuma longa* L. from Uttarakanchal. *J. Essent. Oil Res.* **2006**, *18*, 166–167. [CrossRef]

137. Sharma, S.K.; Singh, S.; Tewari, S.K. Study of leaf oil composition from various accessions of *Curcuma longa* L. grown on partially reclaimed sodic soil. *Int. J. Plant Environ.* **2019**, *5*, 293–296. [CrossRef]

138. Bansal, R.P.; Bahl, J.R.; Garg, S.N.; Naqvi, A.A.; Kumary, S. Differential chemical compositions of the essential oils of the shoot organs, rhizomes and rhizoids in the turmeric *Curcuma longa* grown in indigo-gangetic plains. *Pharm. Biol.* **2002**, *40*, 384–389. [CrossRef]

139. Sharma, R.K.; Misra, B.P.; Sarma, T.C.; Pathak, M.G.; Leclercq, P.A. Essential oils of *Curcuma longa* L. from Bhutan. *J. Essent. Oil Res.* **1997**, *9*, 589–592. [CrossRef]

140. Behura, S.; Sahoo, S.; Srivastava, V.K. Major constituents in leaf essential oils of *Curcuma longa* L. and *Curcuma aromatica* Salisb. *Curr. Sci.* **2002**, *83*, 1312–1313.

141. Ajaiyeoba, E.O.; Sama, W.; Essien, E.E.; Olayemi, J.O.; Ekundayo, O.; Walker, T.M.; Setzer, W.N. Larvicidal activity of turmerone-rich essential oils of *Curcuma longa* leaf and rhizome from Nigeria on *Anopheles gambiae*. *Pharm. Biol.* **2008**, *46*, 279–282. [CrossRef]

142. Essien, E.; Newby, J.; Walker, T.; Setzer, W.; Ekundayo, O. Chemotaxonomic characterization and *in vitro* antimicrobial and cytotoxic activities of the leaf essential oil of *Curcuma longa* grown in Southern Nigeria. *Medicines* **2015**, *2*, 340–349. [CrossRef]

143. Ananya, K.; Sujata, M.; Pande, M.K.; Sanghamitra, N. Essential oils from leaves of micropropagated turmeric. *Curr. Sci.* **2009**, *96*, 1166–1167.
Plants 2021, 10, 44

144. Chaaban, A.; Richardi, V.S.; Carrer, A.R.; Brum, J.S.; Cipriano, R.R.; Martins, C.E.N.; Navarro-Silva, M.A.; Deschamps, C.; Molento, M.B. Cuticular damage of Lucilia cuprina larvae exposed to Curcuma longa leaves essential oil and its major compound α-phellandrene. Data Br. 2018, 21, 1776–1778. [CrossRef] [PubMed]

145. Chaaban, A.; Gomes, E.N.; Richardi, V.S.; Martins, C.E.N.; Brum, J.S.; Navarro-Silva, M.A.; Deschamps, C.; Molento, M.B. Essential oil from Curcuma longa leaves: Can an overlooked by-product from turmeric industry be effective for myiasis control? Ind. Crops Prod. 2019, 132, 352–364. [CrossRef]

146. Sindhu, S.; Chempakam, B.; Leela, N.K.; Bhai, R.S. Chemoprevention by essential oil of turmeric leaves (Curcuma longa L.) on the growth of Aspergillus flavus and aflatoxin production. Food Chem. Toxicol. 2011, 49, 1188–1192. [CrossRef] [PubMed]

147. Parveen, Z.; Nawaz, S.; Siddique, S.; Shahzad, K. Composition and antimicrobial activity of the essential oil from leaves of Curcuma longa L. Kasur variety. Indian J. Pharm. Sci. 2013, 75, 117–122. [CrossRef]

148. Kulappangkorn, W.; Mai-Leang, S. Effect of plant nutrition on turmeric production. Procedia Eng. 2012, 32, 166–171. [CrossRef]

149. Dosoky, N.S.; Satyal, P.; Setzer, W.N. Variations in the volatile compositions of Curcuma species. Foods 2019, 8, 53. [CrossRef]

150. Yadav, R.; Lal, R.K.; Chanoitya, C.S.; Shanker, K.; Gupta, P.; Shukla, S. Prediction of genetic variability and character contribution using path analysis in turmeric (Curcuma longa L.) germplasm. Trends Phytochem. Res. 2019, 3, 91–100.

151. Chowdhury, J.U.; Nandi, N.C.; Bhuiyan, M.N.I.; Mobarak, M.H. Essential oil constituents of the rhizomes of two types of Curcuma longa of Bangladesh. Bangladesh J. Sci. Ind. Res. 2008, 43, 259–266. [CrossRef]

152. Pal, K.; Chowdhury, S.; Dutta, S.K.; Chakraborty, S.; Chakraborty, M.; Pandit, G.K.; Dutta, S.; Paul, P.K.; Choudhury, A.; Majumder, B.; et al. Analysis of rhizome colour content, bioactive compound profiling and ex-situ conservation of turmeric genotypes (Curcuma longa L.) from sub-Himalayan terai region of India. Ind. Crops Prod. 2020, 150, 112401. [CrossRef]

153. Kumar Rai, S.; Kumar Rai, K.; Pandey, N.; Kumari, A.; Tripathi, D.; Shashi Pandey. R. Varietal performance of turmeric (Curcuma longa L.) with special reference to curcumin and essential oil content under climatic conditions of Indogangetic plains. Veg. Sci. 2016, 43, 36–43.

154. Shashidhar, M.D.; Hegde, N.K.; Hiremath, J.S.; Kukunoor, J.S.; Srikanthprasad, D.; Patil, R.T. Evaluation of turmeric (Curcuma longa L.) genotypes for yield, curcumin and essential oil content in northern dry zone of Karnataka. J. Pharmacogn. Phytochem. 2018, SP3, 130–134.

155. Sahoo, A.; Kar, B.; Jena, S.; Dash, B.; Ray, A.; Sahoo, S.; Nayak, S. Qualitative and quantitative evaluation of rhizome essential oil of different eight cultivars of Curcuma longa (Turmeric). J. Essent. Oil-Bear. Plants 2019, 22, 239–247. [CrossRef]

156. Plotto, A. Turmeric: Post-Production Management; Mazaud, F., Röttger, A., Steffel, K., Eds.; Food and Agricultural Organization of the United Nations (FAO): Rome, Italy, 2004; pp. 1–21.

157. Oyemitan, I.A.; Elusiyan, C.A.; Onifade, A.O.; Akanmu, M.A.; Oyedeji, A.O.; McDonald, A.G. Neuropharmacological profile and chemical analysis of fresh rhizome essential oil of Curcuma longa (turmeric) cultivated in Southwest Nigeria. Toxicol. Rep. 2017, 4, 391–398. [CrossRef] [PubMed]

158. Naz, S.; Ilyas, S.; Parveen, Z.; Javed, S. Chemical analysis of essential oils from turmeric (Curcuma longa) rhizome through GC-MS. Asian J. Chem. 2010, 22, 3153–3158.

159. Gonçalves, G.M.S.; Barros, P.P.; da Silva, G.H.; Fedes, G.R. The essential oil of Curcuma longa rhizomes as an antimicrobial and its composition by Gas Chromatography/Mass Spectrometry. Rev. Ciências Médicas 2019, 28, 1–10. [CrossRef]

160. Sandeep, I.; Sanghamitra, N.; Sujata, M. Differential effect of soil and environment onmetabolic expression of tumeric. Exp. Biol. 2008, 406–411.

161. Sandeep, I.S.; Kuanar, A.; Akbar, A.; Kar, B.; Das, S.; Mishra, A.; Sial, P.; Naik, P.K.; Nayak, S.; Mohanty, S. Agroclimatic zone based metabolic profiling of turmeric (Curcuma longa L.) for phytochemical yield optimization. Ind. Crops Prod. 2016, 85, 229–240. [CrossRef]

162. Akbar, A.; Kuanar, A.; Patnaik, J.; Mishra, A.; Nayak, S. Application of artificial neural network modeling for optimization and prediction of essential oil yield in turmeric (Curcuma longa L.). Comput. Electron. Agric. 2018, 148, 160–178. [CrossRef]

163. Garg, S.N.; Bansal, R.P.; Gupta, M.M.; Kumar, S. Variation in the rhizome essential oil and curcumin contents and oil quality in the land races of turmeric Curcuma longa of North Indian plains. Flavour Fragr. J. 1999, 14, 315–318. [CrossRef]

164. Singh, G.; Kapoor, I.P.S.; Singh, P.; de Heluani, C.S.; de Lampasona, M.P.; Catalan, C.A.N. Comparative study of chemical composition and antioxidant activity of fresh and dry rhizomes of turmeric (Curcuma longa Linn.). Food Chem. Toxicol. 2010, 48, 1026–1031. [CrossRef]

165. Gounder, D.K.; Lingamallu, J. Comparison of chemical composition and antioxidant potential of volatile oil from fresh, dried and cured turmeric (Curcuma longa) rhizomes. Ind. Crops Prod. 2012, 38, 124–131. [CrossRef]

166. Monton, C.; Luprasong, C.; Charoenchai, L. Convection combined microwave drying affect quality of volatile oil compositions and quantity of curcuminoids of turmeric raw material. Rev. Bras. Farm. 2019, 29, 434–440. [CrossRef]

167. Monton, C.; Luprasong, C.; Charoenchai, L. Acceleration of turmeric drying using convection and microwave-assisted drying technique: An optimization approach. J. Food Process. Preserv. 2019, 43, e14096. [CrossRef]

168. El-Hawaz, R.F.; Grace, M.H.; Janbey, A.; Lila, M.A.; Adelberg, J.W. In vitro mineral nutrition of Curcuma longa L. affects production of volatile compounds in rhizomes after transfer to the greenhouse. BMC Plant Biol. 2018, 18, 122. [CrossRef]

169. De Ferrari, M.P.S.; dos Queiroz, M.S.; de Andrade, M.M.; Alberton, O.; Gonçalves, J.E.; Gazim, Z.C.; Magalhães, H.M. Substrate-associated mycorrhizal fungi promote changes in terpene composition, antioxidant activity, and enzymes in Curcuma longa L. acclimatized plants. Rhizophora 2020, 13, 100191. [CrossRef]
170. De Ferrari, M.P.S.; da Cruz, R.M.S.; dos Queiroz, M.S.; de Andrade, M.M.; Alberton, O.; Magalhães, H.M. Efficient ex vitro rooting, acclimatization, and cultivation of Curcuma longa L. from mycorrhizal fungi. J. Crops Sci. Biotechnol. 2020, 23, 469–482. [CrossRef]

171. Blázquez, M.A. Role of natural essential oils in sustainable agriculture and food preservation. J. Sci. Res. Rep. 2014, 3, 1843–1860. [CrossRef]

172. Wallia, S.; Saha, S.; Tripathi, V.; Sharma, K.K. Phytochemical biopesticides: Some recent developments. Phytochem. Rev. 2017, 16, 989–1007. [CrossRef]

173. Wallia, S.; Saha, S.; Kundu, A. Environment friendly pesticides based on essential oils and their constituents. In Pesticides and Pests; Parmar, B.S.; Singh, S.B.; Wallia, S., Eds.; Cambridge Scholars Publishing: Newcastle, UK, 2019; pp. 241–263.

174. Garay, J. Review of essential oils: A viable pest control alternative. J. Hum. Ecol. 2020, 71, 13–22. [CrossRef]

175. Raveau, R.; Fontaine, J.; Sahraoui, A.L.-H. Essential oils as potential alternative biocontrol products against plant pathogens and weeds: A review. Foods 2020, 9, 365. [CrossRef]

176. Werrie, P.-Y.; Durenne, B.; Delaplace, P.; Fauconnier, M.-L. Phytotoxicity of essential oils: Opportunities and constraints for the development of biopesticides. A review. Foods 2020, 9, 1291. [CrossRef] [PubMed]

177. Rawat, S. Food Spoilage: Microorganisms and their prevention. Pelagia Res. Libr. Asian J. Plant Sci. Res. 2015, 5, 47–56.

178. Salas, M.L.; Mounier, J.; Valence, F.; Coton, M.; Thierry, A.; Coton, E. Antifungal microbial agents for food biopreservation—A review. Microorganisms 2017, 5, 37. [CrossRef] [PubMed]

179. Amza, J. Seed borne fungi; food spoilage, negative impact and their management: A review. Food Sci. Qual. Manag. 2018, 81, 70–79.

180. Savicka, B.; Egbuna, C. Pests of agricultural crops and control measures. In Natural Remedies for Pest, Disease and Weed Control; Egubna, C., Savicka, B., Eds.; Elsevier Inc.: Cambridge, MA, USA, 2020; pp. 1–16. [CrossRef]

181. WHO. Aflatoxins. Available online: https://www.who.int/foodsafety/FSDigest_Aflatoxins_EN.pdf (accessed on 18 September 2020).

182. Abbas, M.; Naz, S.A.; Shafique, M.; Jabeen, N.; Abbas, S. Fungal contamination in dried fruits and nuts: A possible source of mycosis and mycotoxicosis. Pak. J. Bot. 2019, 51, 1523–1529. [CrossRef]

183. Tournas, V.H. Spoilage of vegetable crops by bacteria and fungi and related health hazards. Crit. Rev. Microbiol. 2005, 31, 33–44. [CrossRef]

184. Kumar, V.; Iqbal, N. Post-harvest pathogens and disease management of horticultural crop: A brief review. Plant Arch. 2020, 20, 2054–2058.

185. Schmidt, M.; Zannini, E.; Lynch, K.M.; Arendt, E.K. Novel approaches for chemical and microbiological shelf life extension of cereal crops. Crit. Rev. Food Sci. Nutr. 2019, 59, 3395–3419. [CrossRef]

186. Brauer, V.S.; Rezende, C.P.; Pessoni, A.M.; De Paula, R.G.; Rangappa, K.S.; Nayaka, S.C.; Gupta, V.K.; Almeida, F. Antifungal agents in agriculture: Friends and foes of public health. Biomolecules 2019, 9, 521. [CrossRef]

187. Badawy, M.E.I.; Abdelgaleil, S.A.M. Composition and antimicrobial activity of essential oils isolated from Egyptian plants against plant pathogenic bacteria and fungi. Ind. Crops Prod. 2014, 52, 776–782. [CrossRef]

188. Nikkhah, M.; Hashemi, M.; Najafi, M.B.H.; Farhoosh, R. Synergistic effects of some essential oils against fungal spoilage on pear fruit. Int. J. Food Microbiol. 2017, 257, 285–294. [CrossRef] [PubMed]

189. Hu, F.; Tu, X.F.; Thakur, K.; Hu, F.; Li, X.L.; Zhang, Y.S.; Zhang, J.G.; Wei, Z.J. Comparison of antifungal activity of essential oils from different plants against three fungi. Food Chem. Toxicol. 2019, 134, 110821. [CrossRef] [PubMed]

190. Arasu, M.V.; Viyarahagavan, P.; Ilavenil, S.; Al-Dhabi, N.A.; Nayaka, S.C.; Gupta, V.K.; Almeida, F. Essential oil of four medicinal plants and protective properties in plum fruits against the spoilage bacteria and fungi. Ind. Crops Prod. 2019, 133, 54–62. [CrossRef]

191. Atif, M.; Ilavenil, S.; Devanesan, S.; AlSalhi, M.S.; Choi, K.C.; Vijayaraghavan, P.; Alfuraydi, A.A.; Alanazi, N.F. Essential oils of two medicinal plants and protective properties of jack fruits against the spoilage bacteria and fungi. Ind. Crops Prod. 2020, 147, 112239. [CrossRef]

192. Singh, G.; Singh, O.P.; Maurya, S. Chemical and biocidal investigations on essential oils of some Indian Curcuma species. Prog. Cryst. Growth Charact. 2002, 45, 75–81. [CrossRef]

193. Akarchariya, N.; Sirilun, S.; Jursigivat, J.; Chansakaowa, S. Chemical profiling and antimicrobial activity of essential oil from Curcuma aeruginosua Roxb., Curcuma glans K. Larsen & J. Mood and Curcuma cf. xanthorrhiza Roxb. collected in Thailand. Asian Pac. J. Trop. Biomed. 2017, 7, 881–885. [CrossRef]

194. Jena, S.; Ray, A.; Sahoo, A.; Panda, P.C.; Nayak, S. Deeper insight into the volatile profile of essential oil of two Curcuma species and their antioxidant and antimicrobial activities. Ind. Crops Prod. 2020, 155. [CrossRef]

195. Péret-Almeida, L.; da Naghetini, C.C.; de Nunan, E.A.; Junqueira, R.G.; Glória, M.B.A. In vitro antimicrobial activity of the ground rhizome, curcuminoid metabolites and essential oil of Curcuma longa L. Cien. e Agrotecno. 2008, 32, 875–881. [CrossRef]

196. Kavas, N.; Kavas, G. Use of turmeric (Curcuma longa L.) essential oil added to an egg white protein powder-based film in the storage of Çökekese cheese. J. Food Chem. Nanotechnol. 2017, 3, 105–110. [CrossRef]

197. Jeleń, H.; Wasowicz, E. Volatile fungal metabolites and their relation to the spoilage of agricultural commodities. Food Rev. Int. 1998, 14, 391–426. [CrossRef]

198. Hu, Y.; Luo, J.; Kong, W.; Zhang, J.; Logricco, A.F.; Wang, X.; Yang, M. Uncovering the antifungal components from turmeric (Curcuma longa L.) essential oil as Aspergillus flavus fumigants by partial least squares. RSC Adv. 2015, 5, 41967–41976. [CrossRef]
Plants 2021, 10, 44

199. Saju, K.A.; Venugopal, M.N.; Mathew, M.J. Antifungal and insect-repellent activities of essential oil of turmeric (Curcuma longa L.). Curr. Sci. 1998, 75, 660–662.

200. Marin, S.; Guynot, M.E.; Schachts, V.; Arbones, J.; Ramos, A.J. Aspergillus flavus, Aspergillus niger, and Penicillium corylophilum spoilage prevention of bakery products by means of weak-acid preservatives. Food Microbiol. Saf. 2002, 67, 2271–2277. [CrossRef]

201. Gougouli, M.; Koutsoumanis, K.P. Risk assessment of fungal spoilage: A case study of Aspergillus niger on yogurt. Food Microbiol. 2017, 65, 264–273. [CrossRef]

202. Mustapha, F.A.; Ji, J.; Raikhan, N.H.N.; Sharif, Z.I.M.; Yusof, N.M. Response surface methodology analysis towards biodegradability and antimicrobial activity of biopolymer film containing turmeric oil against Aspergillus niger. Food Control 2019, 99, 106–113. [CrossRef]

203. Vanasco, J.A.C.; Mahecha, P.V.; Andrade-Mahecha, M.M. Essential oil turmeric (Curcuma longa) antifungal agent as in edible coatings applied to pumpkin minimally processed. Rev. Ciências Agrárias 2017, 40, 641–654. [CrossRef]

204. Oranusi, S.; Olarewaju, S. Mycoflora and aflatoxin contamination of some foodstuffs. Int. J. Biotechnol. Allied Fields 2013, 1, 9–18.

205. Embaby, E.M.; Awni, N.M.; Abdel-galil, M.M.; El-gendy, H.I. Mycoflora and mycotoxin contaminated some juices. J. Agric. Technol. 2015, 11, 693–712.

206. Saleem, A.R. Mycobacteria and molecular detection of Aspergillus flavus and A. parasiticus aflatoxin contamination of strawberry (Fragaria annanassa Duch.) fruits. Arch. Phytopathol. Plant Prot. 2017, 50, 982–996. [CrossRef]

207. García-Díaz, M.; Patiño, B.; Vázquez, C.; Gil-Serna, J. A novel niosome-encapsulated essential oil formulation to prevent Aspergillus flavus growth and aflatoxin contamination of maize grains during storage. Toxins 2019, 11, 646. [CrossRef]

208. Li, Z.; Tang, X.; Shen, Z.; Yang, K.; Zhao, L.; Li, Y. Comprehensive comparison of multiple quantitative near-infrared spectroscopy models for Aspergillus flavus contamination detection in peanut. J. Sci. Food Agric. 2019, 99, 5671–5679. [CrossRef] [PubMed]

209. Mitchell, N.J.; Bowers, E.; Hurbner, C.; Wu, F. Potential economic losses to the US corn industry from aflatoxin contamination. Food Addit. Contam. Part A 2016, 33, 540–550. [CrossRef] [PubMed]

210. Alshannaq, A.F.; Gibbons, J.G.; Lee, M.K.; Han, K.H.; Hong, S.B.; Yu, J.H. Controlling aflatoxin contamination and propagation of Aspergillus flavus by a soy-fermenting Aspergillus oryzae strain. Sci. Rep. 2018, 8, 1–14. [CrossRef] [PubMed]

211. Ferreira, F.D.; Mossini, S.A.G.; Ferreira, F.M.D.; Arrot, J.V. Essential oil turmeric (Curcuma longa) antifungal agent as in edible coatings applied to pumpkin minimally processed. J. Essent. Oil-Bear. Plants 2010, 425–431. [CrossRef]

212. Chappell, M.; Knox, G.; Stamps, R.H. Alternatives to Synthetic Herbicides for Weed Management in Container Nurseries; The Institute of Food and Agricultural Sciences (IFAS): Quincy, FL, USA, 2012; pp. 1–6.

213. Ibrahim, N.F.; Mohd, M.H.; Nor, N.M.I.M.; Zakaria, L. Mycotoxigenic potential of Fusarium species associated with pineapple diseases. Arch. Phytopathol. Plant Prot. 2020, 53, 217–229. [CrossRef]

214. Munkvold, G.P. Fusarium species and their associated mycotoxins. In Mycotoxigenic Fungi: Methods and Protocols, Methods in Molecular Biology; Moretti, A., Sucea, A., Eds.; Springer: New York, NY, USA, 2017; Volume 1542, pp. 51–106. [CrossRef]

215. Kumar, K.N.; Venkataramana, M.; Allen, J.A.; Chandranayaka, S.; Murali, H.S.; Batra, H.V. Role of Curcuma longa L. essential oil in controlling the growth and zearalenone production of Fusarium graminearum. LWT Food Sci. Technol. 2016, 69, 522–528. [CrossRef]

216. Senouci, H.; Benyelles, N.G.; Dib, M.E.A.; Costa, J.; Muselli, A. Chemical composition and combinatory antifungal activities of Ammodytes verticillata, Allium sativum and Curcuma longa essential oils against four fungi responsible for tomato diseases. Comb. Chem. High Throughput Screen. 2020, 23, 196–204. [CrossRef]

217. Bagoo, S.; Maiti, R.; Arora, P.; Jha, P.; Srivastava, A. Allelochemicals as bioherbicides—Present and Perspectives. In Herbicides—Current Research and Case Studies in Use; Price, A.J., Kelto, J.A., Eds.; IntechOpen: London, UK, 2013; pp. 517–542. [CrossRef]

218. Alshannaq, A.F.; Gibbons, J.G.; Lee, M.K.; Han, K.H.; Hong, S.B.; Yu, J.H. Controlling aflatoxin contamination and propagation of Aspergillus flavus by a soy-fermenting Aspergillus oryzae strain. Sci. Rep. 2018, 8, 1–14. [CrossRef] [PubMed]

219. Chen, Z.; Tang, X.; Shen, Z.; Yang, K.; Zhao, L.; Li, Y. Comprehensive comparison of multiple quantitative near-infrared spectroscopy models for Aspergillus flavus contamination detection in peanut. J. Sci. Food Agric. 2019, 99, 5671–5679. [CrossRef] [PubMed]

220. Mitchell, N.J.; Bowers, E.; Hurbner, C.; Wu, F. Potential economic losses to the US corn industry from aflatoxin contamination. Food Addit. Contam. Part A 2016, 33, 540–550. [CrossRef] [PubMed]

221. Alshannaq, A.F.; Gibbons, J.G.; Lee, M.K.; Han, K.H.; Hong, S.B.; Yu, J.H. Controlling aflatoxin contamination and propagation of Aspergillus flavus by a soy-fermenting Aspergillus oryzae strain. Sci. Rep. 2018, 8, 1–14. [CrossRef] [PubMed]

222. Ramezani, S.; Saharkhiz, M.J.; Ramezani, F.; Fotokian, M.H. Use of essential oils as bioherbicides. J. Agric. Technol. 2015, 11, 693–712.

223. Saleem, A.R. Mycobacteria and molecular detection of Aspergillus flavus and A. parasiticus aflatoxin contamination of strawberry (Fragaria annanassa Duch.) fruits. Arch. Phytopathol. Plant Prot. 2017, 50, 982–996. [CrossRef]

224. Tworkoski, T. Herbicide effects of essential oils. Weed Sci. 2002, 50, 425–431. [CrossRef]

225. Ramezani, S.; Saharkhiz, M.J.; Moein, M.; Khoshghalb, H. Phytotoxic effects of several essential oils on two weed species and tomato. Biocatal. Agric. Biotechnol. 2018, 13, 204–212. [CrossRef]

226. Bessette, S.M. Herbcidal Composition Containing Plant Essential Oils and Mixtures or Blends Thereof. U.S. Patent 2002/0193250 A1, 19 December 2002.

227. Szymonidou, A.; Petrotos, K.; Vasilakoglou, I.; Gkoutsidis, P.; Karkanta, F.; Lazaridou, A. Natural Herbicide Based on Essential Oils and Formulated as Wettable Powder. Patent EP 2684457 A1, 15 January 2014.

228. CABl. Portulaca oleracea. Available online: https://www.cabi.org/isc/datasheet/43609 (accessed on 29 September 2020).
Plants 2021, 10, 44

229. Jin, R.; Wang, Y.; Liu, R.; Gou, J.; Chan, Z. Physiological and metabolic changes of purslane (Portulaca oleracea L.) in response to drought, heat, and combined stresses. Front. Plant Sci. 2016, 6, 1123. [CrossRef]

230. DiTomaso, J.M.; Kyser, G.B. Italian and Perennial Ryegrass; Weed Research and Information Center: Davis, CA, USA, 2013; pp. 1–3.

231. CABI. Lolium multiflorum (Italian Ryegrass). Available online: https://www.cabi.org/isc/datasheet/74001 (accessed on 29 September 2020).

232. Bajwa, A.A.; Jabran, K.; Shahid, M.; Ali, H.H.; Chauhan, B.S. Ehsanullah Eco-biology and management of Echinochloa crus-galli. Crops Prot. 2015, 75, 151–162. [CrossRef]

233. Zhang, Z.; Gu, T.; Zhao, B.; Yang, X.; Peng, Q.; Li, Y. Effects of common Echinochloa varieties on grain yield and grain quality of rice. Field Crops Res. 2017, 203, 163–172. [CrossRef]

234. Ibáñez, M.D.; Blázquez, M.A. Ginger and turmeric essential oils for weed control and food crop protection. Plants 2019, 8, 59. [CrossRef]

235. Prakash, B.; Singh, P.; Kedia, A.; Singh, A.; Dubey, N.K. Efficacy of essential oil combination of Curcuma longa L. and Zingiber officinale Rosc. As a postharvest fungitoxicant, aflatoxin inhibitor and antioxidant agent. J. Food Saf. 2012, 32, 279–288. [CrossRef]

236. De Melo, S.C.; De Sá, L.E.C.; de Oliveira, H.L.M.; Trettel, J.R.; da Silva, P.S.; Gonçalves, J.E.; Gazim, Z.C.; Magalhães, H.M. Chemical constitution and allelopathic effects of Curcuma zedoaria essential oil on lettuce achenes and tomato seeds. Aust. J. Crop Sci. 2017, 11, 906–916. [CrossRef]

237. Global Invasive Species Database. Cortaderia selloana. Available online: http://www.iucnisd.org/gsid/species.php?sc=373 (accessed on 29 September 2020).

238. Comité Científico; Comité de Flora y Fauna Silvestres. Solicitud de Dictamen Por Parte de la Junta de Extremadura Sobre la Pertinencia de la Denegación de la Propuesta de una Empresa que Pretende Llevar a Cabo un “Ensayo de Investigación con Nicotiana Glauca- TAPCS1 Como Cultivo Energético Para la Producción”; Ministerio de Agricultura, Alimentación y Medio Ambiente: Madrid, Spain, 2016; pp. 1–6.

239. Estrategia de Gestión, Control y Posible Erradicación del Plumero de la Pampa (Cortaderia selloana) y otras Especies de Cortada- ria. Available online: https://www.miteco.gob.es/es/biodiversidad/publicaciones/estrategia_cortaderia_tcm30-478424.pdf (accessed on 29 September 2020).

240. Khattak, S.; Rehman, S.U.; Shah, H.U.; Ahmad, W.; Ahmad, M. Biological effects of indigenous medicinal plants Curcuma longa and Alpinia galanga. Fitoterapia 2005, 76, 254–257. [CrossRef]

241. Abbasi, K.; Shah, A.A. Biological evaluation of turemeric (Curcuma longa). Int. J. Curr. Microbiol. Appl. Sci. 2015, 4, 236–249.

242. Akbar, A.; Ali, I.; Samiullah; Ullah, N.; Khan, S.A.; Rehman, Z.; Rehman, S.U. Drought affects aquaporins gene expression in important pulse legume chickpea (Cicer arietinum L.). Pak. J. Bot. 2019, 51, 1129–1135. [CrossRef]

243. Pop, A.; Muste, S.; Ponceau, A.; Chis, S.; Man, S.; Salanta, L.; Marc, R.; Muresan, A.; Martis, G. Herbs and spices in terms of food preservation and shelf life. Hop Med. Plants 2019, 27, 57–65. [CrossRef]

244. Nguyen, M.P. Synergistic effect of turmeric (Curcuma longa), galanga (Alpinia galanga) powder and lemongrass (Cymbopogon citratus) essential oil as natural food preservatives during white hard clam (Meretrix lyrata). Orient. J. Chem. 2020, 36, 195–200. [CrossRef]

245. Guerra, A.M.S.; Hoyos, C.G.; Velásquez-Cock, J.A.; Acosta, L.V.; Rojo, P.G.; Giraldo, A.M.V.; Gallego, R.Z. The nanotech potential of turmeric (Curcuma longa L.) in food technology: A review. Crit. Rev. Food Sci. Nutr. 2020, 60, 1842–1854. [CrossRef]
256. Priya, R.; Prathapan, A.; Raghu, K.G.; Menon, A.N. Chemical composition and in vitro antioxidative potential of essential oil isolated from Curcuma longa L. leaves. Asian Pac. J. Trop. Biomed. 2012, 2, S695–S699. [CrossRef]

257. Ilyasov, I.R.; Beloborodov, V.L.; Selivanova, I.A.; Terekhov, R.P. ABTS/PP decolorization assay of antioxidant capacity reaction pathways. Int. J. Mol. Sci. 2020, 21, 1131. [CrossRef]

258. Kedare, S.B.; Singh, R.P. Genesis and development of DPPH method of antioxidant assay. J. Food Sci. Technol. 2011, 48, 412–422. [CrossRef]

259. Cheng, Z.; Li, Y. Reducing power: The measure of antioxidant activities of reductant compounds? Redox Rep. 2004, 9, 213–217. [CrossRef]

260. Shahwar, D.; Raza, M.A.; Bukhari, S.; Bukhari, G. Ferric reducing antioxidant power of essential oils extracted from Eucalyptus and Curcuma species. Asian Pac. J. Trop. Biomed. 2012, 2, S1633–S1636. [CrossRef]

261. Zaki, N.; Fa, M.; Yusof, N.; Jai, J. Turmeric (Curcuma longa L.) Oil as Antioxidant Agent in Starch-Based Edible Coating Film for Fresh-Cut Fruits. Available online: https://www.semanticscholar.org/paper/Turmeric-%28-Curcuma-longa-L-%29-Oil-as-Antioxidant-in-NAM-Mustapha/9404fbe5dcc4eef231abf07d6a9b2d070f331d8?p2df (accessed on 19 November 2020).

262. Ibáñez, M.D.; López-Gresa, M.P.; Lisón, P.; Rodrigo, I.; Bellés, J.M.; González-Mas, M.C.; Blázquez, M.A. Essential oils as natural antimicrobial and antioxidant products in the agrifood industry. Nereis. Interdiscip. Ibero-Am. J. Methods Model. Simul. 2020, 12, 55–69. [CrossRef]

263. Thakam, A.; Saewan, N. Chemical composition of essential oil and antioxidant activities of Curcuma petiolata Roxb. rhizomes. Adv. Mater. Res. 2012, 506, 393–396. [CrossRef]

264. Dawidowicz, A.L.; Olszowy, M. Influence of some experimental variables and matrix components in the determination of antioxidant properties by β-carotene bleaching assay: Experiments with BHT used as standard antioxidant. Eur. Food Res. Technol. 2010, 231, 835–840. [CrossRef]