Curcuma longa L. Essential Oil

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Curcuma longa L. rhizome essential oil is a valuable product in pharmaceutical industry due to its wide beneficial health effects.

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][5][6][7][8][9][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][15][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, desmethoxycurcumin and bisdesmethoxycurcumin, 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][24][25][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][29][30][31][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][37][38][39][40][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][43][44][45][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 savory, 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][57][58][59][60][61][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.

2. 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 1), which is normally used for a sesquiterpenoid analysis [63] alone or combined with Gas Chromatography-Flame Ionisation detector (GC-FID) [64][65][66] 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 [67].

As a general rule, oxygenated sesquiterpenes have been identified as the predominant ones (Table 1) and the principal reason of the biological activity of turmeric essential oil [68]. Concretely, turmerones (α-, β- and ar-) represent the major and the most distinctive individual components [69][70] (Table 1 and Figure 1). They give interesting properties to *C. longa* essential oil, such as anticancer, anti-inflammatory, antioxidant and the prevention of dementia [71][72][73][74][75]. Even they enhance the bioavailability and activity of other important turmeric components like curcumin [76][77][78]. 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 1). Many authors have reported about the therapeutic potential of ar-turmerone and its numerous benefits for human health [75]. Lee demonstrated its antibacterial activity against human pathogens like *Clostridium perfringens* and *Escherichia coli* [79]. In the same year, he also reported a higher inhibitory effect than aspirin in platelet aggregation induced by collagen and arachidonic acid [80]. Other researchers have proposed ar-turmerone as a natural anticancer and cancer-preventive agent, being considered the α,β-unsaturated ketone of the molecule, the principal pharmacophore, for this activity [51][81][82][83]. ar-Turmerone has also been observed as useful in the prevention and attenuation of inflammatory diseases like psoriasis and neuronal ones [84][85].

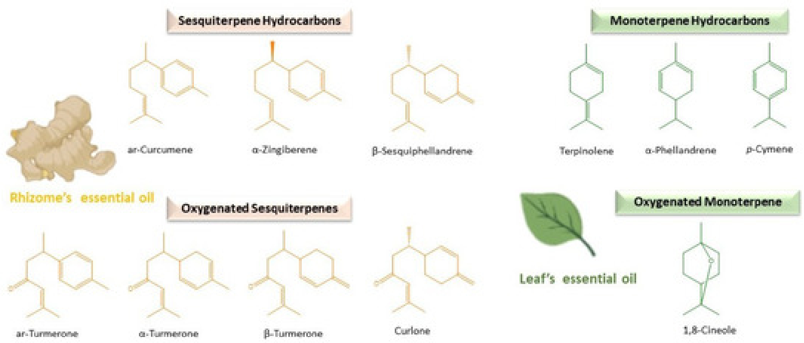

Figure 1. Main compounds found in the rhizomes and leaves of turmeric essential oils.

Oxygenated sesquiterpenes also constitute the predominant group in the essential oils obtained from the rhizome of other species included in the genus *Curcuma* [86]. 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. leucorhiza;* β-elemenone in *C. nankunshanensis* var. *nanlingensis*; xanthorrhizol in *C. xanthorrhiza* and velleral in *C. attenuata* [86][87][88][89][90]. 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 [91]. 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][92].

The sesquiterpenoids are generally followed by smaller quantities of sesquiterpene hydrocarbons in *C. longa* rhizome oil (Table 1 and Figure 1). This group is characterised by great structural diversity, providing a variety of fragrances and characteristic aromas to the essential oil [93]. Specifically, monocyclic bisabolane derivatives with a C_6-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 C_9-ring fused to a cyclobutane ring [94]. 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%) [86].

The amount of monoterpene hydrocarbons and oxygenated monoterpenes are usually lower in most samples of rhizome essential oil of *C. longa* (Table 1). Contrarily, they constitute the most abundant group in the rhizome oil of other different *Curcuma* spp., such as *C. amada* [95], as well as in the essential oils obtained from the aerial parts of *C. longa* [17][96][97][98][99]. 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 [100]. 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 1) [70], being also usually found in the essential oils of the aerial parts of *C. longa* *p*-cymene, α-terpinene, myrcene and pinenes (Table 1) [96][97][99][101][102]. However, in samples of *C. longa* grown in Nigeria, the leaf essential oil was dominated by turmerones, like in rhizomes (Table 1) [103][104]. In addition, important concentrations of C_8-aldehyde (20.58%) were found in the essential oil of *C. longa* leaves in a high-altitude research station in Odisha, India [102]. The concentration of these compounds can be increased by enhancing the leaf biomass production [105].

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 *Cochliomya macellaria*, causative agents of myasis in humans and animals, as well as against *Lucilia cuprina* [106][107], 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 [108][109].

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 [86][110][111]. 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 [112]. 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. [113]. Indeed, the rhizome colour is closely related to the beneficial properties of *C. longa* [114]. 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 [115][116][117].

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][70]. In India, the region of production determines the type of turmeric [118]. 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 [103][119], 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 [97]. Turmerones still are also the predominant compounds in samples from Faisalabad (Pakistan) and Turkey [65][120]. 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%) [66][68][121].

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][122][123][124]. 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 [125]. 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 [101]. 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 [126]. 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 [127], 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 [128][129]. The sun and mechanical drying coexist as drying methods of *C. longa* rhizomes [118]. 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 [129].

Table 1. 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, GC-FID: Flame Ionisation Detector, SFE: Supercritical Fluid Extraction, SWE: Supercritical Water Extraction and: GC-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%), *epi*-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	[71]
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%)	[130]
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%)	[130]
Rhizomes	Brazil	Steam distillation assisted by microwave (SDAM)	GC-MS	0.9%	-	[130]
Rhizomes	Brazil	SDAM + CG	GC-MS	1.45%	-	[130]
Powdered dried rhizome	Serbia	Hydrodistillation Clevenger	GC-MS and GC-FID	0.3 cm^3/100 g	ar-turmerone (22.7%), turmerone (26%) and curlone (16.8%)	[65]

Part of Turmeric	Origin	Method of Extraction	Analysis	Yield	Main Components	Ref.
Rhizomes	Pakistan	Hydrodistillation	GC-MS	0.673%	ar-turmerone (25.3%), α-turmerone (18.3%) and curlone (12.5%)	[120]
Powdered rhizomes	Thailand	Hydrodistillation Clevenger	GC-MS	-	ar-turmerone (43–49%), turmerone (13–16%) and curlone (17–18%)	[128] [129]
Dried rhizomes	Brazil	SFE	GC-MS	0.5–6.5 g/100 g	ar-turmerone (20%) and ar-, α- and β–turmerones (~75%)	[131]
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%)	[65]
Dried rhizomes	Brazil	Steam distillation	GC-MS and CG-FID	0.46%	ar-turmerone (~12.8%), α-turmerone and β –turmerone (~4.1%)	[65]
Dried rhizomes	China	Steam distillation	GC-MS	4.50% *w/w*	ar-turmerone (11.81%)	[86]
Dried rhizomes	Nigeria	Hydrodistillation Clevenger	GC-MS	1.33% *w/w*	ar-turmerone (44.4%), α-turmerone (20.8%), β–turmerone (26.5%)	[103]
Dry rhizomes	India	Hydrodistillation Clevenger	GC-MS	2.9%	ar-turmerone (21.4%), α-santalene (7.2%) and ar-curcumene (6.6%)	[126]
Dried rhizomes	India	Hydrodistillation Clevenger	GC-MS	3.05 ± 0.15%	ar-turmerone (30.3%), α-turmerone (26.5%), β–turmerone (19.1%)	[129]
Cured rhizomes	India	Hydrodistillation Clevenger	GC-MS	4.45 ± 0.37%	ar-turmerone (28.3%), α-turmerone (24.8%), β–turmerone (21.1%)	[129]
Dried root	-	SFE	GC-MS	2–5.3 wt%	ar-turmerone (31–67.1%), β–turmerone (2–37.9%), α-turmerone (0–21.3%)	[132]
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]

Part of Turmeric	Origin	Method of Extraction	Analysis	Yield	Main Components	Ref.
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%), curlone (5.6%), turmerone (4.4%), zingiberene (4.01%), ar-curcumene (4.01%), dehydrocurcumene (2.0%)	[133]
Fresh rhizome	Malaysia	SFE	GC-MS	-	ar-turmerone (10.84–21.50%), turmerone (36.14–45.68%) and curlone (21.27–22.30%)	[134]
Fresh rhizomes	Iran	SWE	GC-MS	0.98%	ar-turmerone (62.88%), curcumin (10.49%), β–sesquiphellandrene (9.62%), α-phellandrene (6.50%)	[135]
Fresh rhizomes	Ecuador	Steam distillation	GC-FID and GC-MS	0.8% *v/w*	ar-turmerone (45.5%) and α-turmerone (13.4%)	[66]
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%)	[96]
Fresh mature rhizomes	Bhutan	Hydrodistillation Clevenger	GC-MS	2–5.5%	α-turmerone (30–32%), ar-turmerone (17–26%) and β–turmerone (15–18%)	[101]
Fresh rhizome	India	Steam distillation	-	2.03–6.50%	-	[118]
Fresh rhizomes	India	Hydrodistillation Clevenger	GC-MS	1.8–3.73 mL/plant	ar-turmerone (39.5–45.5%), curlone (9.8–11.7%), α-phellandrene (5.5–7.7%), eucalyptol (3.2–5.5%), β–himachalene (1.6–5.5%) and copen-11-ol (2.3–5.4%)	[119]

Part of Turmeric	Origin	Method of Extraction	Analysis	Yield	Main Components	Ref.
Fresh rhizomes	Nigeria	Hydrodistillation Clevenger	GC-MS	10.5 g (0.7% *w/w*)	Turmerone (35.9%), α-phellandrene (15.5%), curlone (12.9%), 1,8-cineole (10.3%) and ar-turmerone (10.0%)	[119]
Fresh rhizomes	Brazil	Hydrodistillation Clevenger	GC-MS	0.70%	Zingiberene (11%), sesquiphellandrene (10%), β–turmerone (10%) and α-curcumene (5%)	[121]
Mature fresh rhizomes	India	Hydrodistillation Clevenger	GC-MS	1.4%	ar-turmerone (24.4%), α-turmerone (20.5%) and β–turmerone (11.1%)	[128]
Fresh rhizomes	India	Hydrodistillation Clevenger	GC-MS	3.52 ± 0.23%	α-turmerone (33.5%), ar-turmerone (21.0%), β–turmerone (18.9%)	[129]
Semi dried leaves and fresh rhizomes	India	Continuous water circulation with steam distillation	GC-MS	Leaves: 2.75–2.83% Rhizomes: 2.38–2.48%	Rhizome: Bisabolene (0.4%), ar-curcumene (2.3%), zingiberene (4.01%), dehydrocurcumene (2.0%), ar-turmerone (15.8%), turmerone (4.4%) and curlone (5.6%)	[136]
Semi-ripened and dried leaves	India	Water distillation techniques	GC-MS	0.25–0.28% *v/w*	Terpinolene (33.0–57.6%), 1,8-cineole (1.9–7.9%), α-terpinene (1.7–3.9%), α-phellandrene (1.4–3.1%)	[36]
Partially senescenced leaves	India	Hydrodistillation Clevenger	GC-MS	-	α-phellandrene, *p*-cymene, α-terpinolene, 1,8-cineole, *p*-cymen-8-ol	[99]
Dried leaves	Nigeria	Hydrodistillation Clevenger	GC-MS	0.67% *w/w*	ar-turmerone (63.4%), α-turmerone (13.7%), β–turmerone (12.6%)	[103]
Dried leaves	Nigeria	Hydrodistillation Clevenger	GC-MS	0.67% *w/w*	ar-turmerone (63.4%), α-turmerone (13.7%), β–turmerone (12.6%)	[104]
Leaves	Bhutan	Hydrodistillation Clevenger	GC-MS	0.3–0.42%	α-phellandrene (18.2%), 1,8-cineole (14.6%) and *p*-cymene (13.3%)	[101]

Part of Turmeric	Origin	Method of Extraction	Analysis	Yield	Main Components	Ref.
Leaves	India	Hydrodistillation Clevenger	GLC	1.32%	α-phellandrene (38.24%), C8-aldehyde (20.58%), 1,8-cineole (8.64%), α-pinene (2.88%) and β–pinene (2.36%)	[102]
Leaves	Pakistan	Hydrodistillation Reverse dean-stark method	GC-MS	145%	Eucalyptol (10.27%), β–pinene (3.57%), 2-methylisoborneol (2.91%), limonene (2.73%), β–phellandrene (2.49%)	[105]
Fresh leaves	India	Hydrodistillation Clevenger	GC-MS	0.2–1.9%	α-Phellandrene (30.82–39.85%), terpinolene (25.74–26.59%) and eucalyptol (7.52–7.66%)	[39]
Fresh leaves	India	Hydrodistillation Clevenger	GC-MS	0.65%	α-phellandrene (53.4%), terpinolene (11.5%) and 1,8-cineole (10.5%)	[43]
Fresh leaves	India	Hydrodistillation Clevenger	GC-MS	0.53%	α-phellandrene (9.1%), terpinolene (8.8%), 1,8-cineole (7.3%) and undecanol (7.1%)	[44]
Roughly crushed fresh leaves	France	Steam distillation	GC-MS and GC-FTIR	0.5%	Terpinolene (77%), 1,8-cineole (4.6%), α-terpinene (3.7%), α-phellandrene (2.8%), myrcene (1.4%) and δ-3-carene (1.1%)	[96]
Fresh leaves	India	Steam distillation	GC-MS	0.15%	Terpinolene (71.2%), 1,8-cineole (6.2%), *p*-cymen-9-ol (4.2%)	[98]
Fresh leaves and stems	Colombia	Steam distillation	GC-MS	-	Turmerone (36.9%), α-turmerone (18.9%) and β–turmerone (13.6%)	[68]
Fresh aerial parts	India	SFE	GC-MS	2.8%	*p*-cymene (25.4%), 1,8-cineole (18%), *cis*-sabinol (7.4%), β–pinene (6.3%)	[97]
Roughly crushed fresh flowers	France	Steam distillation	GC-MS and GC-FTIR	0.15%	Terpinolene (67.4%), 1,8-cineole (4.6%), α-terpinene (4.4%), α-phellandrene (3.6%), myrcene (2%) and zingiberene (1.3%)	[96]

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% [110]. 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 [137]. 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 [138][139]. 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 [118].

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.

3. 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 [140][141][142][143][144][145]. 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).

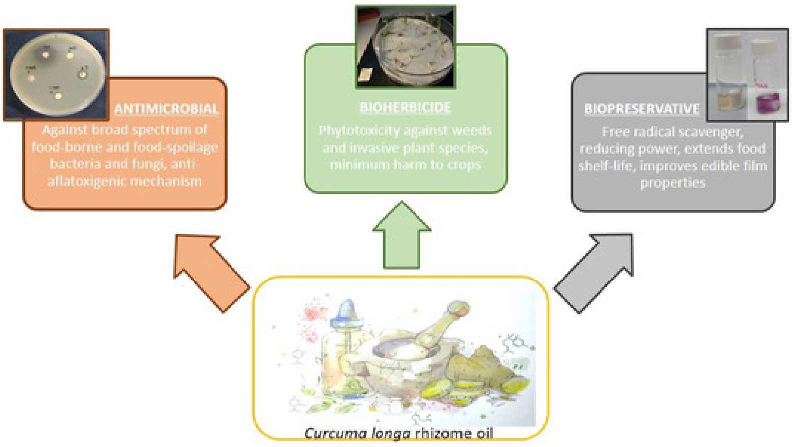

Figure 2. Representation of the roles that *Curcuma longa* rhizome oil can play in the safer and more sustainable emerging agri-food industry: antimicrobial, herbicidal and antioxidant activities.

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