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MINI REVIEW

An insight into the main chemical constituents, extraction methods, and functional properties of essential oils from Moringa plants: a mini-review

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Abstract

Moringa plants are recognized as multipurpose plant material due to their high content of bioactive constituents such as phenolic compounds, proteins, and essential oils, among others. This mini-review provided interesting and innovative information collected from the Scopus, Science Direct, and Google Scholar databases on the main chemical constituents of essential oils extracted from different moringa plants. In addition, it highlighted the different conventional and non-conventional techniques applied in the extraction of essential oils from different parts of moringa plants, and the functional properties of these essential oils are reviewed. Thus, this overview offers, for the first time, a compilation of published information on these topics, which may be useful in food and pharmaceutical products.

1. Introduction

Native to northern India but currently cultivated in many tropical and arid regions around the world, moringa plants belong to the sole genus of the *Moringaceae* family, containing 13 different species, and they can be found in many countries in Africa, Arabia, South East Asia, the Pacific and Caribbean Islands, and South America (Ogunbinu, Flamini, Cioni, Adebayo *et al*., 2009; Nibret and Wink, 2010; Marrulfo *et al.,* 2013; Hussein *et al*., 2014; Elsayed *et al*., 2015; Otunola and Afolayan, 2018; Senthilkumar *et al*., 2020). *Moringa oleifera* also called the miracle tree, drumstick tree, ben oil tree, horseradish tree, or benzoil tree, is the most representative, studied, and widely known member of this family (Zhao and Zhang, 2013; Abdel-Waretch and Lohakare, 2021; George *et al*., 2021). It has shown an extensive variety of functional properties, which have been attributed to the bioactive compounds present in its vegetative structures (*e.g.,* pods, roots, leaves, flowers, and seeds) (Hussein *et al.,* 2014; Otunola and Afolayan, 2018). However, other species such as *M. peregrina*, *M. stenopetala*, and *M. concanensis* have also been recognized for having economic importance due to their industrial applications. Moreover, they also are suitable sources of bioactive compounds with several functional properties and applications in the food industry (Saucedo -Pompa *et el*., 2018; Senthilkumar *et al*., 2020). Generally, these plants are used in traditional herbal medicine for the treatment of different diseases (*i.e*., stomach disorders, diabetes, and hypertension) around the world. In addition, they have shown antimicrobial, antioxidant, hypo-cholesteremic, and other properties (Chuang *et al*., 2007; Nibret and Wink, 2010; Kayode and Afolayan *et al*., 2015). Some of these functional properties can be attributed to the chemical components of the essential oils (EOs), which depend on several factors, including the geographic origin of the moringa plants and the extraction processes. Conventional and non-conventional techniques, such as hydrodistillation and free-solvent microwave extraction, among others, have been successfully used for the recovery of EOs from different plant materials, including moringa plants. This mini-review provided an overview of the chemical characterization of EOs from different parts of moringa species, relevant information associated with their extraction process, the functional properties exhibited by these oils, and their potential applications in food products—information which has not previously been collated in a single publication.

2. Materials and methods

This review was conducted by considering those papers published mainly in the last five years available in

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databases such as Scopus, Science Direct, and Google Scholar. It was built according to searches made using the keywords "Moringa plants essential oils", "*Moringa oleifera* essential oils", and the same words but different moringa species. Studies wherein the whole lipid fraction was extracted (and called "essential oil") from these plant materials were excluded (*e.g.*, Saleem *et al*., 2017). Additional information from these databases was incorporated as required to clarify ideas.

3. Essential oil extraction processes

Conventional methods include hydrodistillation and steam distillation, which are techniques based on the use of hot water, in the former, the plant material is immersed in boiling water, while in the latter, steam is generated and passed through the plant material, thus entraining the volatile compounds. Otherwise, non-conventional methods such as free-solvent microwave extraction, supercritical fluid extraction, and ultrasonic-assisted extraction have been successfully applied to obtain EOs from different parts of moringa plants (Zhao and Zhang, 2013; Otunola and Afolayan, 2018). These techniques have some advantages such as reduced extraction times and higher yields when compared with the conventional methods (Yingngam *et al*., 2021), which aligns with the current trends in EO extraction focusing on the discovery of more efficient methodologies. According to Lucchesi *et al*. (2004), free -solvent microwave extraction is a combination of microwave heating and dry distillation, performed at atmospheric pressure without the addition of any solvent or water. This technique causes a disruption in the cell walls of the sample by the use of microwaves and heating, leading to better and faster release of EOs from plant materials (Idris *et al*., 2020). On the other hand, supercritical fluid extraction is a technique using fluids in conditions that are elevated above their critical point of temperature, which could be affected by special factors such as the temperature, pressure, and extraction time (Zhao and Zhang, 2013; Abharia and Khaneghah, 2020). These techniques have been applied in the extraction of EOs from moringa plants.

All the vegetative parts of moringa plants (*i.e.*, leaves, seeds, barks, roots, and flowers) have been used to obtain EOs with different quality and yields depending on the source and extraction method. The essential oil from these plants is usually extracted by similar protocols, with hydrodistillation and steam distillation being the main techniques applied to obtain these components (Table 1). In most cases, the extraction process is carried out on the dry sample with the use of a Clevenger-type apparatus according to a standard procedure, such as those described in the European Pharmacopoeia Commission (2004) or Mbokanem and Moyo (2019), at the laboratory level. However, no studies at the pilot or industrial level on the extraction of EO from moringa plants were found, which indicates an opportunity for innovative studies in this field.

In most cases reviewed where hydrodistillation and steam distillation techniques were used as the extraction method, the obtained yields of EO were low, ranging from 0.05 to 0.7% depending on the moringa tissue, with the leaves being the most studied part in the examined reports. Jafari *et al*. (2021) reported that the yields of EO extracted from the seeds and leaves of *M. peregrina* increased 2- and 4-fold, respectively, when these plant materials were pre-treated in an ultrasonic bath for 40 min and then distilled in a Clevenger apparatus. This could be due to the implosion of the cavitation bubbles, which produce a shear force that splits the cell, facilitating the release of EOs (Bautista-Hernández *et al*., 2021). Furthermore, with the use of other non-conventional techniques, higher amounts of EO have been recorded. Zhao and Zhang (2013) reported that the extraction yields of EO from *M. oleifera* leaves ranged from 4.0 to 6.3%, depending on the experimental conditions, when supercritical fluid (CO_2) extraction was applied; this is probably due to the relatively low operating temperatures which allow the preservation of the thermally labile compounds in the extracts. In addition, similar results were observed in a recent study that demonstrated that free-solvent microwave extraction can be used to extract EO from different parts of *M. oleifera* (Otunola and Afolayan, 2018). In that study, the authors reported that the highest EO content was present in leaves (3.6%), followed by flowers (≈2.2%), roots (≈2.0%), and bark (≈1.5%). Nevertheless, this effect did not appear in the seeds, as the content of EO was in the same range as that obtained by conventional extraction methods (Kayode and Afolayan, 2015; Otunola and Afolayan, 2018). Therefore, non-convectional techniques are emerging as promising methods for the extraction of EOs from different moringa plant parts and species.

4. Chemical composition of essential oils

Although there seems to be no correlation between the chemical constituents from one study to another, it was observed that monoterpene compounds were present more frequently in the analyzed samples; however, they were present in very small amounts, generally below 1%. Table 1 shows the five most abundant compounds present in EOs extracted from different parts of moringa plants and reported in several studies. From these components and according to the chemical characterization carried out by the authors, the most common family of compounds present in the species of

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Table 1. Essential oils from moringa plants, extraction methods, registered yields, and main chemical components

Moringa species and tissue	Extraction method	Time (mins)	Essential oil yield (%)	Color	Total compounds	Main components	Percentage from the extracted oil	Kind of compound	References
M. oleifera leaves	Steam distillation	NI	0.24	clear brown	44	Pentacosane	17.41	alkane	Chuang *et al.* (2007)
						Hexacosane	11.2	alkane	
						(E)-phytol	7.66	diterpene	
						1-[2,3,6-Trimethyl-phenyl]-2-butanone	3.44	aromatic ketone	
						Benzeneacetaldehyde	2.16	aldehyde	
M. oleifera leaves	Hydrodistillation	NI	0.3	NI	63	α-Phellandrene (menthadiene)	25.2	monoterpene	Ogunbinu, Flamini, Cioni, Adebayo *et al.* (2009)
						p-Cymene	24.9	monoterpene	
						α-Pinene	6.7	monoterpene	
						Myrcene	4.8	monoterpene	
						Limonene	4.1	monoterpene	
M. oleifera leaves	Hydrodistillation	180	0.05	pale yellow	29	Hexacosane	13.9	alkane	Marrufo *et al.* (2013)
						Pentacosane	13.3	alkane	
						Heptacosane	11.4	alkane	
						Nonacosane	10.5	alkane	
						Octacosane	10	alkane	
M. oleifera leaves	Free-solvent microwave extraction	30	3.6	NI	27	Eicosane	17.12	alkane	Otunola and Afolayan (2018)
						Heptacosane	9.13	alkane	
						n-Hexadecanoic acid (palmitic acid)	7.33	fatty acid	
						Dibutyl phthalate	5.19	ester	
						Pentadecanal	4.1	aldehyde	
M. oleifera leaves	Hydrodistillation	180	NI	NI	23	Hexacosane	15.9	alkane	Mbokane and Moyo (2019)
						Pentacosane	12.3	alkane	
						Heptacosane	10.4	alkane	
						Nonacosane	8.5	alkane	
						Octacosane	8	alkane	
M. oleifera leaves	Hydrodistillation	180	NI	NI	18	Ar-turmerone	55.46	sesquiterpene	Abdel-Wareth and Lohakare (2021)
						Curlone	13.94	sesquiterpene	
						Tumerone	5.73	sesquiterpene	
						Hexacosane	5.51	alkane	
						Tetrapentacontane, 1,54-dibromo	3.62	haloalkane	
M. oleifera leaves	Supercritical fluid (CO_2) extraction	60 - 120*	4.0 - 6.34 *	NI	10-12*	Nonacosane	(13.37 - 60.06)*	alkane	Zhao and Zhang (2013)
						Heptacosane	(4.97 - 22.66)*	alkane	
						b-Amyrin	(1.50 - 8.14)*	triterpene	
						Pentacosane	(1.0 - 6.32)*	alkane	
						1,30-Triacontanediol	(0.86 - 10.05)*	fatty alcohol	

NI: Not indicated, *depending on the extraction conditions

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Table 1 (Cont.). Essential oils from moringa plants, extraction methods, registered yields, and main chemical components

Moringa species and tissue	Extraction method	Time (mins)	Essential oil yield (%)	Color	Total compounds	Main components	Percentage from the extracted oil	Kind of compound	References
M. peregrina leaves	Ultrasonic extraction / Hydrodistillation	40 / 180	0.32	NI	27	Farnesyl acetone	22.72	terpene ketone	Jafari *et al.* (2021)
						Oxide 1,6-Octadien-3-ol	11.14	monoterpene	
						α-Terpineol	10.2	monoterpene	
						2(1H)-Naphthalenone	8.55	aromatic hydrocarbons	
						1-Octadecene	6.09	alkene	
M. oleifera seeds	Hydrodistillation	180	0.05	yellow	24	Naphthalene	35.65	aromatic hydrocarbon	Hussein *et al.* (2014)
						Benzene isothiocyanatomethyl	34.89	benzene derivative	
						Butylated Hydroxytoluene	6.12	Phenol derivative	
						Estragole	4.5	Phenyl propanoid	
						11-Octadecenoic acid, methyl ester	4.01	fatty acid ester	
M. oleifera seeds	Free-solvent microwave extraction	30	0.67	faint yellow	26	Cyclopentane	51.5	cycloalkane	Kayode and Afolayan (2015)
						n-Hexadecanoic acid (palmitic acid)	11.14	fatty acid	
						2(1H)-Naphthalenone	8.7	aromatic hydrocarbons	
						2-(E)-decenal	4.37	aldehyde	
						Eicosane	3.1	alkane	
M. oleifera seeds	Hydrodistillation	NI	0.7	faint yellow	16	Tetracosane	34.26	alkane	Kayode and Afolayan (2015)
						Eicosane	19.58	alkane	
						Heptadecane	22.2	alkane	
						n-Hexadecanoic acid (palmitic acid)	8.45	fatty acid	
						Cyclopentane	3.6	cycloalkane	
M. oleifera seeds	Free-solvent microwave extraction	30	0.3	NI	23	Eicosane	21.59	alkane	Otunola and Afolayan (2018)
						Naphthalene	13.41	aromatic hydrocarbon	
						Nerolidol	8.76	sesquiterpene	
						Phthalic acid, isobutylundecyl ester	6.38	phthalic acid ester	
						Dibutyl phthalate	5.19	ester	
M. oleifera seeds	Hydrodistillation	180	0.28	NI	24	Dimethyl-sulfoxide isomers	77.01	sulfoxide	Othman and El-Mongy (2016)
						Oleic Acid, 6-Octadecenoic acid	11.27	fatty acid	
						9-Octadecenoic acid, (E)- cis- Vaccenic acid	3.25	fatty acid	
						n-Hexadecanoic acid, Octadecanoic acid	2.41	fatty acid	
						7- octadecatrienoic acid methyl ester, methyl	2.2	fatty acid derivative	
M. peregrina seeds	Hydrodistillation	420	0.22	light yellowish green	33	Geijerene	33.38	sesquiterpene	Senthilkumar *et al.* (2021)
						Linalool	23.36	monoterpene	
						Caryophyllene oxide	19.28	sesquiterpene	
						n-Hexadecane	12.59	alkane	
						Carvacrol	1.89	monoterpene	

NI: Not indicated, *depending on the extraction conditions

Table 1 (Cont.). Essential oils from moringa plants, extraction methods, registered yields, and main chemical components

Moringa species and tissue	Extraction method	Time (mins)	Essential oil yield (%)	Color	Total compounds	Main components	Percentage from the extracted oil	Kind of compound	References
M. peregrina seeds	Ultrasonic extraction / Hydrodistillation	40 / 180	0.17	NI	33	Isothiocyanic acid	41.44	benzene derivative	Jafari *et al.* (2021)
						n-Dodecane	7.25	alkane	
						Tridecane	6.91	alkene	
						Pentadecan	5.44	alkane	
						Nonyl aldehyde	3.3	aldehyde	
M. stenopetala seeds	Steam distillation	360	0.105	White-gray	11	Benzyl isothiocyanate	54.3	benzene derivative	Nibret and Wink (2010)
						Isobutyl isothiocyanate	16.37	benzene derivative	
						Palmitic acid	14.47	fatty acid	
						Oleic acid	8.13	fatty acid	
						Methyl 9-octadecenoate	1.98	alkene	
M. oleifera flowers	Free-solvent microwave extraction	30	≈ 2.2	NI	25	Eicosane	20.93	alkane	Otunola and Afolayan (2018)
						Nerolidol	12.55	sesquiterpene	
						Heptacosane	12.04	alkane	
						n-Hexadecanoic acid (palmitic acid)	5.9	fatty acid	
						Bicyclo[10.8.0] eicosane, cis-	4.36	cycloalkane	
M. oleifera flowers	Hydrodistillation	180	0.28	colorless	29	Nonanal	17.03	aldehyde	Balogun *et al.* (2017)
						Geranyl geraniol	13.5	diterpenoid	
						Eicosane	12.3	alkane	
						α-Terpineol	7.2	monoterpene	
						Hexahydro farnesyl acetone	5.1	sesquiterpene	
M. oleifera barks	Free-solvent microwave extraction	30	≈ 1.5	NI	13	Naphthalene	18.4	aromatic hydrocarbon	Otunola and Afolayan (2018)
						2-Bornanone (Camphor)	10.65	monoterpene	
						Nonanal	10.36	aldehyde	
						2-Isopropoxyphenol	9.68	aromatic eter	
						Eucalyptol	8.06	monoterpene	
M. oleifera roots	Free-solvent microwave extraction	30	≈ 2.0	NI	11	Benzene, isothiocyanate methyl	35.83	isothiocyanate	Otunola and Afolayan (2018)
						Dibutyl phthalate	24.95	phthalic acid	
						Benzyl nitrile	14.17	cyanides	
						Benzaldehyde	13.43	aldehyde	
						1-Ascorbic acid 2,6-dihexadecanoate	2.97	vitamin	

NI: Not indicated, *depending on the extraction conditions

moringa was alkanes, followed by other compounds in the order monoterpenes > fatty acids and derivatives > sesquiterpenoids = aldehydes > isothiocyanates > aromatic hydrocarbons > other uncommon components. Besides this, from the general chemical characterizations of EOs made by the authors, the representative compounds from each family were eicosane, α-terpineol and isomers, hexadecanoic acid and derivatives, caryophyllene and derivatives, nonanal, benzene isothiocyanato methyl, and naphthalene, respectively (Figure 1). The best results for EO characterization from moringa plants were reported by Ogunbinu, Flamini, Cioni, Adebayo *et al*. (2009), who elucidated 63 molecules from *M. oleifera* leaves. Interestingly, in that study, terpenoids (monoterpenes) dominated (82%) the chemical components of the EO from this plant material. For more details on the chromatographic conditions and identification, readers are referred to a study previously published by the same research group (Ogunbinu, Flamini, Cioni, Ogunwande *et al*., 2009). This characterization was made according to findings further reported by Senthilkumar *et al*. (2020), who reported that the sesquiterpenoids geijerene and caryophyllene oxide comprised more than 52% of the chemical constituents in the EO of *M. peregrina* seeds. In addition, sesquiterpenoids ar-turmerone, curlone, and turmerone represented 75% of the components present in the EO extracted from the leaves of *M. oleifera* (Abdel-Wareth and Lohakare, 2021). Likewise, the terpenoids farnesyl acetone, oxide 1,6-octadien-3-ol, and a-terpienol were the most abundant (44%) compounds in the leaves of *M. peregrina* (Jafari *et al*. 2021). However, as aforementioned, alkanes eicosane (Kayode and Afolayan, 2015; Otunola and Afolayan, 2018), nonacosane (Zhao and Zhang), hexacosane (Marrulfo *et al*., 2013; Mbokane and Moyo, 2019), and pentacosane (Chuang *et al*., 2007) were the most dominant components in different parts of *M. oleifera*. Finally, other uncommon compounds such as benzyl isothiocyanate, naphthalene, and isothiocyanic acid were reported as the main components in the EOs of *M. stenopetala*, *M. oleifera*, and *M. peregrina* cultivated in Ethiopia, India, and Iran, respectively (Nibret and Wink, 2010; Hussein *et al*., 2014). The variation in the chemical composition and amounts of EO extracted from moringa plants can be attributed to genetic factors among the species, but also climate conditions, rainfall, or the geographic origin of the plants (Ríos, 2016). In addition, the selection of the extraction method, the extraction parameters, and the selection source (different moringa parts) could be important factors (Zhao and Zhang, 2013; Kayode and Afolayan, 2015; Otunola and Afolayan, 2018).

5. Functional properties of essential oils

5.1 Antioxidant activity

Usually, the antioxidant properties of moringa plants are attributed to the presence of high amounts of polyphenolic compounds (Saucedo-Pompa *et al.*, 2018; Castro-López *et al.*, 2020). Thus, some studies have been conducted to evaluate the antioxidant potential of EOs extracted from *M. oleifera* and *M. peregrina*. For example, Marrulfo *et al.* (2013) proved that hydrocarbon -rich EO from *M. oleifera* has scavenging properties against DPPH$^{\bullet}$ free radicals; however, the flavonoids luteolin and quercetin present in this oil seem to be responsible for these properties. Moreover, the EO from *M. peregrina* seeds was recently identified as a better antioxidant agent than butylated hydroxyanisole and ascorbic acid due to its ability to inhibit several free radicals, conferred by the presence of gerijernene

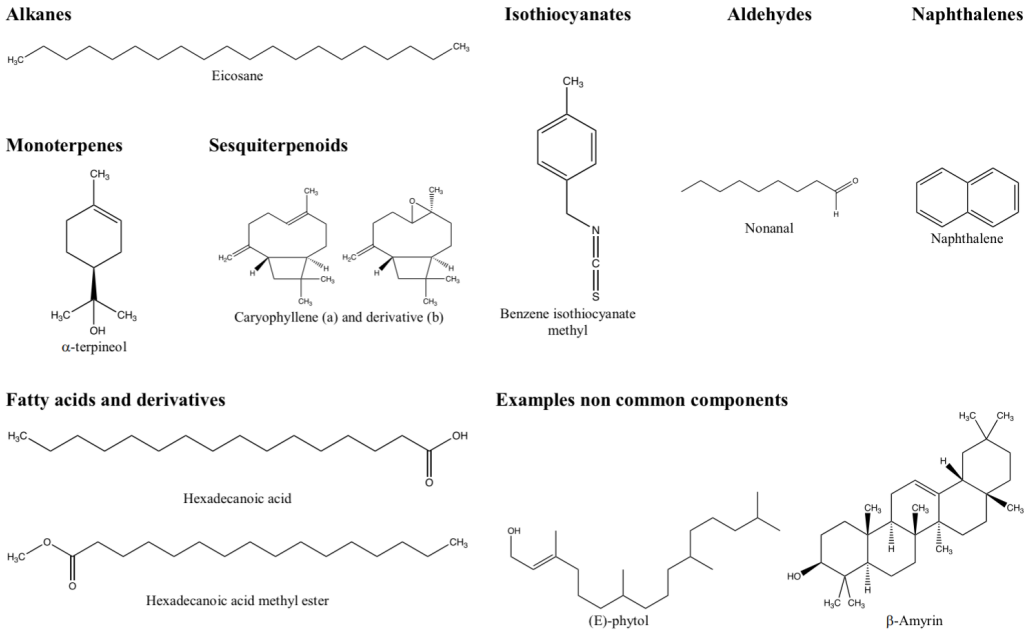

Figure 1. Main representative families and compounds present essential oils from moringa plants

(sesquiterpene) and linalool (monoterpene). It can thereby be considered a potential substitute for the synthetic antioxidant agents used in the food industry (Senthilkumar *et al.,* 2020). This supports findings previously reported by Hussein *et al.* (2014), who reported that EO from *M. oleifera* seeds has antioxidant properties, such as reducing power and chelating activity against ferrous ions, and free-radical scavenging activities associated with the presence of volatile terpenoid-type compounds such as thymol and eugenol, which are capable of donating hydrogen atoms with electrons to stabilize free radicals. Hence, EOs from moringa plants could be used as antioxidant agents providing colour stabilization and preventing lipid oxidation in raw beef, as demonstrated for other molecules extracted from *M. oleifera* leaves (Shah *et al.,* 2015). Thus, EOs from moringa plants have great potential for use in a wide variety of foodstuffs due to their antioxidant properties. However, despite these results, detailed studies are needed to confirm the possible application of the EOs in a food matrix.

5.2 Cytotoxic activity

Cancer is one of the most progressive and harmful diseases undermining human health, and the most common treatment for this degenerative illness involves chemotherapy, radiotherapy, and surgical intervention (Elsayed *et al.,* 2015). However, scientific evidence has proven that EOs from moringa plants could potentially play an important role as anticancer agents. According to Hussein *et al.* (2014), EO from *M. oleifera* seeds has a very toxic effect on the viability of several cell lines, such as breast carcinoma (IC_{50} = 10.2 µg/mL), colon carcinoma (IC_{50} = 17.9 µg/mL), hepatocellular carcinoma (IC_{50} = 10.0 µg/mL), larynx carcinoma (IC_{50} = 20.6 µg/mL), and cervical carcinoma (IC_{50} = 16.5 µg/mL), in a concentration-dependent manner after 24 hrs of incubation. This could be related to the antioxidant properties of this EO, which has been proven to have good scavenging properties against several free radicals (*e.g.*, superoxide, hydrogen peroxide, and hydroxyl radicals), as well as chelating and reducing properties, which combat oxidative stress mechanisms. In addition, the cell morphology and adhering capacity of cells could be affected by the addition of seed oil, leading to cell detachment and death, as suggested by Elsayed *et al.* (2015).

On the other hand, the effect of the EO from *M. olifera* seeds on the lethality of brine shrimp larvae was described by Kayode and Afolayan *et al.* (2015). In this study, the recorded median lethal concentration (LC_{50}) values were higher than those reported for tumour cell inhibition and were dependent on the extraction method used to obtain the EOs. According to the authors, for EO extracted by a solvent-free microwave method, LC_{50} = 2906.8 µg/mL, and for EO extracted by hydrodistillation, LC_{50} = 3495.8 µg/mL on the viability of brine shrimp larvae, which could be related to the differences in the number of oxygenated compounds found in each sample. This opens the opportunity to explore this oil as a pharmaceutical agent. Finally, it was suggested that the inhibitory effects on the shrimp larvae were the result of synergic activity among the components present in these EOs (*i.e.*, cyclopentane, *n*-hexadecanoic acid, 2-(*E*)-decenal, eicosane, 1,5-dimethyl-2-pyrrolecarbonitrile, 1-nonanol, tetracosane, heptadecane, phenanthrene-carboxylic acid, phthalic acid, diethyldithiophosphoric acid, and acetamide). Accordingly, the EOs from moringa plants could be further studied regarding their antitumor and cell viability effects in order to explain those mechanisms of action.

5.3 Antimicrobial activity

It has been reported that EOs from moringa plants are capable of inhibiting the growth of several microorganisms such as fungal strains and Gram-positive (G+) and -negative (G–) bacteria, which have been recognized as microorganisms of interest for the food and health industries.

Marrufo e*t al.* (2013) reported microbial properties of EO from *M. oleifera* against G+ strains (*i.e.*, *Bacillus cereus* and *Staphylococcus aureus*) and G– strains (*i.e.*, *Escherichia coli* and *Pseudomonas aeruginosa*). The authors reported that *B. cereus* was the most sensitive strain, followed by *P. aeruginosa* and *E. coli*, showing inhibition halos at 2, 5, and 10 µg of EO per plate, respectively. However, *S. aureus* was not inhibited by any EO concentration used. Moreover, steam distillate of *M. oleifera* was used to inhibit the growth of *E. coli, S. aureus, K. pneumoniae, P. aeruginosa*, and *B. subtillis* (Prashit *et al.,* 2010), with inhibition rates from 49.16 to 75.43 % using a nutrient broth containing steam distillate at 5 %.

Essential oils from the flowers, leaves, seeds, bark, and roots of *M. oleifera* were extracted and successfully used to inhibit the growth of *Enterococcus faecalis*, *Klebsiella pneumoniae*, *Proteus vulgaris*, and *Shigella flexineri,* with MIC values ranging from 1.25 to >5 mg/mL (Otunola and Afolayan, 2018). However, *S. aureus*, *Streptococcus pyogenes*, *Pseudomonas aeruginosa*, and *Serratia marcescens* showed no susceptibility to any of the EOs. The intake of EO from moringa at a concentration of 9-12 % increased by 70 % the disease resistance of *Clarias gariepinus* against *Aeromonas hydrophila,* an opportunistic bacterium (Mbokane and Moyo, 2019). These findings suggest that incorporating

EOs into the diet could reduce the incidence of disease outbreaks on *C. gariepinus* farms.

Within its antimicrobial activity, fungal inhibition by EOs from moringa has been reported. Chuang *et al.* (2007) used EO against several fungi dermatophytes responsible for many skin diseases, showing MIC (mg/mL) values of 1.6, 0.8, 0.2, and 0.4 for *Trichophyton rubrum*, *Trichophyton mentagrophytes*, *Epidermophyton floccosum*, and *Microsporum canis*, respectively. Marrufo *et al.* (2013) evaluated the growth of five strains of agro-food interest (*Penicillium aurantiogriseum*, *P. expansum*, *P. citrinum*, *P. digitatum*, and *Aspergillus niger*) in the presence of EO from *M. oleifera*. The authors observed inhibition halos in all fungal strains at the lower EO concentration (2 µg/disk), except for *P. aurantiogriseum*, which was only inhibited at 5 µg/disk. Using the Poison food technique, steam distillate of MO was shown to inhibit the growth of *A. niger*, *A. oryzae*, *A. terreus*, and *A. nidulans,* with inhibition rates of 46.51, 26.31, 23.07, and 16.21%, respectively (Prashid *et al.* 2010). This antifungal effect was attributed to the presence of an essential oil fraction in the distillate; however, further studies are needed to elucidate the active fraction from the moringa steam distillate. According to Jantapan *et al.* (2017), EO obtained by cold-pressing from moringa seed and used against *A. parasiticus* and *A. flavus* showed no significant inhibition at the maximum concentration tested (4 mg/mL). This result may be due to the profile of compounds extracted by the method and parameters used, as well as the source or plant part (Otunola and Afolayan, 2018).

Essential oils contain secondary metabolites able to inhibit bacterial and fungal growth, attributed to an attack of the membrane and cytoplasm, promoting changes in the morphology of the cells and, finally, cellular lysis (Chuang *et al.,* 2007). Generally, the antimicrobial effect is dose-dependent; at low values, it can interfere with enzymes involved in the production of energy, while at higher concentrations, it induces the denaturation of proteins, leading to irreversible cell modification and cell death (Nazarro *et al.,* 2013).

6. Essential oil for food applications

Due to their vast contents of different bioactive compounds, EOs from moringa plants have potential research applications to improve the quality of food products, such as by enhancing the amount of fatty acids in milk and increasing its antioxidant properties. According to the findings reported by Selmi *et al.* (2020), the chemical constituents of EOs from *M. oleifera* can cause some modifications in the proportions of acetate and propionate in the rumen of ewes, increasing the unsaturated fatty acid content (e.g., conjugated linoleic acids) in milk from 25 g/L to 30 g/L after supplementation with 0.6 mL of this oil daily (for 8 weeks). Additional information on the use of EOs from moringa plants in food products was not found, this could be an important reference for future applications of these EOs.

7. Conclusion

Taken together, the results above indicate that the chemical composition of EOs from different parts of moringa plants comprises a diverse group of molecules that could be considered promising for applications in different industries, including the food and pharmaceutical industries. Considering the great diversity of chemical compounds and functional properties of these EOs, further investigations should focus on the effect of the extraction technique on the quality and extraction yield of the EOs from moringa plants and the use of these oils in food products. Despite all the presented data, critical information to confirm the possible application of these EOs in different food matrices, taking into account physicochemical alterations in food products, will need to be obtained in future investigations.

Conflicts of interest

The authors declare no conflicts of interest.

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