Antiparasitic and Antibacterial Functionality of Essential Oils: An Alternative Approach for Sustainable Aquaculture

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Abstract: Using synthetic antibiotics/chemicals for infectious bacterial pathogens and parasitic disease control causes beneficial microbial killing, produces multi-drug resistant pathogens, and residual antibiotic impacts in humans are the major threats to aquaculture sustainability. Applications of herbal products to combat microbial and parasitic diseases are considered as alternative approaches for sustainable aquaculture. Essential oils (EOs) are the secondary metabolites of medicinal plants that possess bioactive compounds like terpenes, terpenoids, phenylpropenes, isothiocyanates, and thiocyanates that can synergistically function against bacterial and parasitic cells and cause cell deformities and organelle dysfunctions. Dietary supplementation of EOs also modulate growth, immunity, and infectious disease resistance in aquatic organisms.

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aquaculture industry. Moreover, research gaps and future approaches to use EOs for sustainable aquaculture practice are also postulated.

**Keywords:** essential oils; parasite; bacteria; aquaculture; immune enhancer; medicinal plants

1. Introduction

Farming of aquatic plants and animals is generally known as aquaculture, and the annual growth of this rapidly expanding food industry is 4.5%, accounting for a value of 243.26 billion USD [1] to meet up the protein demand of ever increasing world population. This important industry is also generating jobs, income, and providing 50% of global fish consumption [2,3]. Due to the increase of consumer demand, aquaculture technique has been shifted from extensive to super-intensive; intensification of aquaculture needs a higher amount of artificial feed supply, water treatment and reuse, and high stocking density resulting in aquatic environmental degradation [4–6]. Mounting of stress and quality deterioration of living environment increases the activity and virulence of infectious and opportunistic microbial pathogens [7], decrease immunity and immune-related gene transcription of aquatic animals [8], and elevate uni and multicellular parasitic infestation [9]; finally, initiate infectious diseases outbreak along with the death of cultured species. Gonzales, et al. [10] reported global aquaculture loss of 1.05 to 9.58 billion USD/year due to infectious diseases and parasitic attacks.

To eliminate diseases and parasitic attacks in the aquaculture industry, different synthetic antibiotics, chemical drugs, vaccines, and chemotherapeutics are being used at high rates from year after year [11,12]. Using of these chemical substances cause mass killing of beneficial aquatic bacteria [13], produce multi-drugs resistant pathogens [14], and leaving residues in fish which can be transmitted to human [15,16]. These problems are the most concerning aquaculture sustainability [17,18], and infectious diseases and parasitic infestation treatment with natural substances/compounds are the demanding sustainable aquaculture features [19].

The use of medicinal plants and their derivatives in aquaculture is increasing day by day all over the world because of having biodegradable properties [20–24], availability and ease to cultivate, and do not accumulate in animal tissues as a residue [25,26]. Essential oils (EOs) are the secondary metabolites of medicinal plants and possess bioactive properties to be used as a phytotherapeutic agent for sustainable aquaculture [27,28]. Terpens, terpenoids, phenylpropenes, and isothiocyanates are the key chemical groups identified in EOs [29]. EOs mainly penetrate and act upon the membrane and cytoplasm of bacteria to inhibit their action mechanisms by altering cell morphology and organelles deformities [30,31]. Generally, Gram-positive bacteria are more sensitive to EOs than Gram-negative due to lipoteichoic acids in cell membranes that might facilitate the penetration of EOs hydrophobic compounds [32]. According to Carson, et al. [33], EO comprises different compounds that have no specific cellular target in parasites. Monoterpens α-pinene and sabinene of EOs have proved mentionable antiprotozoal activity. Moreover, synergistic effects of different compounds in EOs are another key feature that showed a higher mode of action relative to individual compounds. EOs cause leakage of potassium ions and cytoplasmic content of parasitic cells due to hydrophobicity and cell permeability, which cause cell morphology alteration and cessation of parasitic activity [34]. Staining with fluorocromes SYBR-14 and propidium iodide confirmand the plasma membrane damage in *Ichthyophthirius multifiliis* by the action of *Varronia curassavica* derived EOs [35].

Different microbial and parasitic diseases are the major threats to the aquaculture industry. Application of nanoemulsions EOs or other herbal products to combat microbial [36,37] and parasitic [9,25] diseases is considered a new alternative approach for sustainable aquaculture. Extensive research activities were performed for the identification and characterization of EOs effects for the fish and shellfish preservation and shelf life
elongation \[38,39\], modulation of growth, immunity, and infectious disease resistance in commercially cultured fish species \[35,40,41\], against different pathogenic microbial activity \[42,43\] and destruction and retardation of fish parasitic activity \[9,10\]. In the fisheries and aquaculture sector, EOs act as a natural preservative \[44\], stress-reducing agent \[45\], herbal anesthetics \[46\], and oregano herb and medicinal plant as immunomodulators \[26\] and immunostimulants \[47\]. However, no study was conducted to identify EOs antiparasitic and antimicrobial properties for sustainable aquaculture.

Although natural EOs have enough potential for sustainable aquaculture, EOs have high volatility and can be decomposed by exposure to heat, humidity, light, and oxygen to lose effectiveness \[48\]. Application to the EOs in their oil form render it subjected to degradation during processing, storage, and handling \[49\]. The use of nano-encapsulated EOs becomes a promising trend in the field of EOs applications \[50\], especially in the aquaculture sectors \[51\], protecting the volatilization, low stability, low solubility in water, and associated problems of using EOs \[52\]. Nanoemulsion technology is currently solving the effectiveness disruption problems of EOs in aquaculture. This technology also protects EOs from the digestive enzyme’s actions in the intestine.

The main focus of this article is to identify EOs antimicrobial and antiparasitic properties that can be used for sustainable aquaculture practices. Moreover, EOs effects for aquaculture species growth, immunomodulation, and infection resistances were also postulated. In addition, research gaps and tentative future research activities are also mentioned to effectively use EOs in sustainable fish culture.

2. EOs as Growth, Immunity, and Disease Resistance Enhancer

Several studies have been conducted to identify EOs growth and immunity elevation property; however, no specific research was conducted to identify the action mechanism of EOs for the alteration of these properties \[28,53–55\]. Jang, et al. \[56\] mentioned the possible reason for growth and feed utilization parameters modulation by EOs is due to elevation of digestive enzymes in the intestines. Moreover, EOs increased the appetite of aquaculture species \[57\] may be another reason. Antioxidant activity increased due to aromatic rings and the position of hydroxyl ion in EOs \[58\]. Modulation of the intestinal microbiome by EOs can be considered one of the possible reasons for the modulation of immune-related genes \[59\]. Significantly, phenolic compounds like thymol and carvacrol modulate innate immunity through two possible ways i) direct action on host tissue ii) influence on the intestinal microbial community \[60\].

A 60-day experiment was conducted with dietary supplementation with bitter lemon \((C. limon)\) \[61\], and sweet orange peels \((C. sinensis)\) \[62\] originated EOs in Mozambique tilapia \((Oreochromis mossambicus)\). In both cases, EOs elevated innate immune parameters \(NBT, WBCs, lysozyme, and myeloperoxidase activity\) and decreased serum/blood glucose, cholesterol, and triglycerides. \(C. limon\) and \(C. sinensis\) EOs administrated tilapia demonstrated resistance against \(S. iniae\) and \(E. tarda\), respectively. In addition, a similar type of immunomodulation and infection protection of tilapia were also found after \(C. limon\) peel EOs supplementation at \((1, 2, 5, \text{ and } 8\%)\) in \(L. victorianus\) for 28 days \[63\]. However, growth \(\text{WG}\%\) and \(\text{SGR}\) and feed conversion ratio \(\text{FCR}\) modulation in the former study remained unchanged but in the latter two experiments increased significantly (Table 1). The authors claim active compound of EOs \(\text{limonene}\) concentration in the former experiment was 54.4\%, whereas later studies were 94.74 and 81.40, respectively, may be the causal factors of these differences. In Nile tilapia \((O. niloticus)\), lemongrass \((C. citratus)\) and geranium \((P. graveolens)\) \[40\], and Oregano \((O. vulgare)\) \[64\], supplementation increased growth and feed utilization, and resistance against the action of \(A. hydrophila\) and \(V. alginolyticus\), respectively. \(C. citratus\) and \(P. graveolens\) supplemented fishes not only improved immunity but also decreased the concentration levels of intestinal coliforms, \(E. coli\), and \(A. spp.\) Moreover, origanum EOs \((1 \text{ g/kg})\) improved immunity and vibriosis protection in \(T. zilli\) \[65\].
Eight weeks feeding trial with 0.05% of Oregano (O. heracleoticum) originated EOs showed better growth, body indices (VSI, HSI, and CF), and antioxidant property (SOD and CAT) in channel catfish (Ictalurus punctatus) [66]. Carvacrol and thymol are the active substances of oregano EOs; however, in this fish species, O. vulgare originated commercial EOs showed inferior results relative to O. heracleoticum. Silver catfish (Rhamdia quelen) was dietary administrated (2 mL/Kg) with Aloysia triphylla EOs [41] and bath treatment (5 and 10 mg/L) with EOs compound, eugenol [67]. Bath treatment was unable to upregulate hematological and immunological parameters, but dietary administration improved healthy blood cells (leukocyte, lymphocyte, and neutrophil) and protein levels. Most importantly, these two catfish species had increased tolerance against A. hydrophila infection protection after feeding or bath treatment with plant originated EOs.

Eight weeks of feeding with O. vulgare EOs increased both immune and antioxidant properties and resistance against A. hydrophila in Cyprinus carpio [60,64]. EOs increased transcription levels of interleukin (IL)-1β and IL-10 and down-regulated tumor necrosis factor (TNF)-α and transforming growth factor (TGF)-β. Moreover, the increment of digestive enzyme activities and enrichment of beneficial bacterial genera in the intestinal microbial community were also found after EOs supplementation (Table 1). Feeding with O. onites instead of O. vulgare, similarly positive immunity and anti-oxidant activity modulation, and infectious disease protection was found in rainbow trout (Oncorhynchus mykiss) [68]. Further, water extract of Ocimum sanctum leaves increased total RBC, WBC, hemoglobin, and other immune and anti-oxidant parameters in L. rohita [69].
Table 1. Effects of herbal essential oils on growth, immunity, and infectious diseases protection in commercial fish species.

| Aquatic Species                      | Essential Oil                          | Dose and Duration | Influence                                                                 | References                  |
|--------------------------------------|----------------------------------------|-------------------|---------------------------------------------------------------------------|-----------------------------|
| Mozambique tilapia (Oreochromis mossambicus) | Bitter lemon (Citrus limon)            | 0.5, 0.75, and 1% for 60 days | - Growth indices and feed utilization (↑)  
- Nitroblue tetrazolium (NBT), white blood cells (WBCs), Blood total protein, lysozyme, and myeloperoxidase activity (↑)  
- Serum glucose, cholesterol, and triglycerides (↓)  
- Resistance against Edwardsiella tarda (↑) | Baba, et al. [61] |
| O. mossambicus                        | Sweet orange (C. sinensis)              | 0.1, 0.3, and 0.5% for 60 days | - Growth indices and feed utilization (↑)  
- Lysozyme and myeloperoxidase activity, hematological and biochemical variables, i.e., hemoglobin (Hb), hematocrit (Htc), erythrocyte indices, total serum protein, albumin, and globulin (↑)  
- Blood glucose, cholesterol, and triglyceride (↓)  
- Resistance against Streptococcus iniae (↑) | Acar, et al. [62] |
| Labeo victorianus                     | C. limon                               | 1, 2, 5, and 8% for 28 days | - Red blood cells (RBC), WBC, Htc, mean cell haemoglobin (MCH), haemoglobin concentration (MCHC), and neutrophils (↑)  
- Immunoglobulin (IgM), lysozyme activity, and respiratory burst (↑)  
- Resistance against A. hydrophila (↑) | Ngugi, et al. [63] |
| Nile tilapia (O. niloticus)           | Lemongrass (Cymbopogon citratus) and Geranium (Pelargonium graveolens) | 200 and 400 mg/kg for 12 weeks | - Growth indices and feed utilization (↑)  
- Plasma catalase; catalase (CAT), glutathione content, lysozyme activity, and total immunoglobulins; IgM (↑)  
- Malondialdehyde (MDA), total intestinal bacteria, coliforms, Escherichia coli, and Aeromonas spp (↓)  
- Resistance against Aeromonas hydrophila (↑) | Al-Sagheer, et al. [40] |
| O. niloticus                          | Origanum vulgare                       | 5 and 10% for 8 weeks | - Growth indices and feed utilization (↑)  
- Antioxidant activities (↑)  
- Resistance against Vibrio alginolyticus (↑) | Abdel-Latif and Khalil [70] |
Table 1. Cont.

| Aquatic Species                     | Essential Oil     | Dose and Duration                          | Influence                                                                 | References                  |
|-------------------------------------|-------------------|--------------------------------------------|---------------------------------------------------------------------------|-----------------------------|
| Tilapia zillii                      | Origanum          | 1 g/kg for 15 days                        | - RBC, WBC, Hb, and differential leukocyte (↑)                             | Mabrok and Wahdan [65]      |
|                                     |                   |                                            | - Plasma proteases, antiproteases, lysozyme, and bactericidal activities (↑) |                              |
|                                     |                   |                                            | - Resistance against V. anguillarum (↑)                                    |                              |
| Channel catfish (Ictalurus punctatus) | O. heracleoticum  | 0.05% for 8 weeks                         | - Growth performance, hepatosomatic index, visceralosomatic index, and condition factor (↑) | Zheng, et al. [66]          |
|                                     |                   |                                            | - Superoxide dismutase (SOD) and CAT (↑)                                  |                              |
|                                     |                   |                                            | - Resistance against A. hydrophila (↑)                                    |                              |
| Silver catfish (Rhamdia quelen)     | Aloysia triphylla | 2.0 mL/kg for 21 days                     | - Total leukocyte, lymphocyte, and neutrophil counts (↑)                   | dos Santos, et al. [41]     |
|                                     |                   |                                            | - Total blood protein and resistance against A. hydrophila (↑)            |                              |
| R. quelen                           | Eugenol           | Bath (5 and 10 mg/L)                      | - Hematological and immunological parameters (↑)                          | Sutili, et al. [67]         |
|                                     |                   |                                            | - Resistance against A. hydrophila (↑)                                    |                              |
| Common carp (Cyprinus carpio L.)    | O. vulgare        | 0, 5, 10, 15, and 20 g/kg diet for 8 weeks | - SOD, CAT, lysozyme activity, phagocytic activity, and index (↑), and malonaldehyde (MDA) (↓) | Abdel-Latif, et al. [64]    |
|                                     |                   |                                            | - Interleukin- (IL)-1β and IL-10 (↑)                                      |                              |
|                                     |                   |                                            | - Resistance against A. hydrophila (↑)                                    |                              |
| Koi carp (C. carpio)                | O. vulgare        | 0, 500, 1500, and 4500 mg/kg for 8 weeks  | - Protease, amylase, and lipase (↑)                                       | Zhang, et al. [60]          |
|                                     |                   |                                            | - Lysozyme, Complement C3 & C4, SOD, and glutathione peroxidase (↑) and MDA (↓) |                              |
|                                     |                   |                                            | - Tumor necrosis factor (TNF)-α and Transforming growth factor (TGF)-β (↓) |                              |
|                                     |                   |                                            | - Vibrio (↓), Propionibacterium, Brevinena, and Corynebacterium_1 (↑)      |                              |
|                                     |                   |                                            | - Resistance against A. hydrophila (↑)                                    |                              |
| Aquatic Species | Essential Oil       | Dose and Duration       | Influence                                                                                     | References      |
|----------------|---------------------|-------------------------|----------------------------------------------------------------------------------------------|-----------------|
| Rainbow trout  | *O. onites*         | 0.125, 1.5, 2.5, and 3.0 mL/kg for 90 days | - Growth indices and feed utilization (↑)  
- SOD, CAT, and Lysozyme activity (↑)  
- Resistance against *Lactococcus garvieae* (↑) | Diler, et al. [68] |
| *O. mossambicus* | *C. limon*         | 0.5, 0.75, and 1% for 60 days | - Growth indices and feed utilization (↔)  
- Nitroblue tetrazolium (NBT), white blood cells (WBCs), Blood total protein, lysozyme, and myeloperoxidase activity (↑)  
- Serum glucose, cholesterol, and triglycerides (↓)  
- Resistance against *E. tarda* (↑) | Baba, et al. [61] |
| *C. sinensis*  | *O. mossambicus*    | 0.1, 0.3, and 0.5% for 60 days | - Growth indices and feed utilization (↑)  
- Lysozyme and myeloperoxidase activity, hematological and biochemical variables, i.e., hemoglobin (Hb), hematocrit (Htc), erythrocyte indices, total serum protein, albumin, and globulin (↑)  
- Blood glucose, cholesterol, and triglyceride (↓)  
- Resistance against *S. iniae* (↑) | Acar, et al. [62] |
| *C. limon*     | *L. victorianus*    | 1, 2, 5, and 8% for 28 days | - Red blood cells (RBC), WBC, Htc, mean cell haemoglobin (MCH), haemoglobin concentration (MCHC), and neutrophils (↑)  
- Immunoglobulin (IgM), lysozyme activity, and respiratory burst (↑)  
- Resistance against *A. hydrophila* (↑) | Ngugi, et al. [63] |

Variation in the treated fish compared to controls: (↑), significantly increases; (↓), significantly decreased; (♭), no significant change.
3. Essential Oils as Antiparasitic Agents

3.1. Acanthocephalas

*Neoechinorhynchus buttnerae* is an acanthocephalan parasite causing significant economic losses in *Colossoma macropomum* fish in the region of Amazon [71,72]. It was reported that *Mentha piperita*, *Lippia alba*, and *Zingiber officinale* [73] and *Piper hispidinervum*, *Piper hispidum*, *Piper marginatum*, and *Piper callosum* [74] essential oils showed 100% anthelmintic effect on *N. buttnerae*. When EO of *piper hispidinervum* was applied on *N. buttnerae* parasite in 0.78 mg/L concentration for 15 min, it gave the most effective result in terms of dose and time [74] (Table 2).

3.2. Monogeneans

3.2.1. *Anacanthorus spathulatus*, *Notozothecium janauachensis*, and *Mymarothecium boegeri*

*Anacanthorus spathulatus*, *Notozothecium janauachensis*, and *Mymarothecium boegeri* cause significant infections in species belonging to the Serrasalmidae family as *C. macropomum* fish being in the first place [75,76]. Anthelmintic effects of *Cymbopogon citratus*, *Pterodon emarginatus*, *Lippia origanoides*, *Lippia sidoides*, and *Lippia alba* EOs on these three parasites were researched [77]. Among the EOs, the most effective one was *Lippia sidoides*; when applied as 320 mg/L for 10 min, it exhibited 100% efficacy against all three parasites [78] (Table 2).

3.2.2. *Dactylogyrus* spp.

One of the most common parasitic pathogens in cultured freshwater fish is *Dactylogyrus* spp. [79]. Brasil, et al. [9] researched anthelmintic effects of *Lippia alba*, *Lippia origanoides*, and *Lippia sidoides* EOs on *Dactylogyrus minutus* and *Dactylogyrus extensus* parasites; and they detected that when *L. Origanoides* and *L. Sidoides* EOs were applied as 100 mg/L for 5 min, they showed 100% efficacy (Table 2).

3.2.3. *Cichlidogyrus* spp.

*Cichlidogyrus* is the parasite genus that occurs naturally in cichlid fish and has the most species among gill parasites, with its 131 different species known [80]. *Scutogyrus* species can also be dominant in the winter season among fish belonging to the Cichlidae family [81]. de Oliveira Hashimoto, et al. [82] reported that *Lippia sidoides* EO had 100% efficacy against *Cichlidogyrus* spp. and *Scutogyrus longicornis* when applied as 160 mg/L for 1 min 58 s while *Mentha piperita* EO had 100% efficacy when applied as 320 mg/L for 8 min 11 s (Table 2).

3.2.4. *Dawestrema* spp.

*Dawestrema cycloancistrium* and *Dawestrema cycloancistrioides* are two of the most significant parasite types causing death and economic losses in *Arapaima gigas* fish, which are cultured in the region of Amazon [83,84]. Application of *M. piperita* EO as 160 and 320 mg/L for 30 min showed 100% efficacy on *D. cycloancistrium* and *D. cycloancistrioides* parasites [85] (Table 2).

3.2.5. *Gyrodactylus* spp.

*Gyrodactylus* spp. causes economic losses in many cultured fish species. Anthelmintic effects of *Hesperozygis ringens*, *Ocimum gratissimum*, and *Ocimum americanum* [37] and *Ocimum americanum* [86] EOs on *Gyrodactylus* spp. were researched. Only *O. americanum* EO as 50 mg/L for 1 h had the most effective anthelmintic action (98% efficacy) against *Gyrodactylus* spp. [86] (Table 2).
3.3. Trepomonadea

**Hexamita inflata**

*Hexamita inflata* is a flagellated anaerobic protozoan and free-living in fresh and seawater. Moon, et al. [87] reported that *L. angustifolia* and *L. intermedia* EOs as 1 and 0.5% for 30 min exhibited 100% efficacy on *H. inflata* (Table 2).

3.4. Clinostomidae

**Euclinostomum heterostomum**

*Euclinostomum heterostomum* is parasitic trematodes and very common in Europe, Asia, and Africa [88]. It infects muscular tissues and kidneys of freshwater fish [88,89]. *Verbesina alternifolia* and *Mentha piperita* EOs could act on *E. Heterostomum* in high doses and for a long time [90] (Table 2).

3.5. Oligohymenophorea

**Ichthyophthirius multifiliis**

*Ichthyophthirius multifiliis* is the most famous virulent ciliated protozoan ectoparasite that invades the skin, fins, and gills of fish. de Castro Nizio, et al. [35] indicated that *Varronia curassavica* EO showed 100% efficacy against *I. multifiliis* trophont and tomont when applied as 10 mg/L and 50 mg/L for one h, respectively. *Hyptis mutabilis* (10 mg/L for 30 min) [91] and *Melaleuca alternifolia*, *Lavandula angustifolia*, and *Mentha piperita* (455 µL/L for 1 h) [92] EOs applications were also found to be effective on *I. multifiliis* (Table 2).
Table 2. Essential oils as antiparasitic agents.

| Parasitic Pathogens | Essential Oil | Concentrations | Elimination Time/Effectiveness | Concentration/Elimination Percentage | References |
|---------------------|---------------|----------------|-------------------------------|--------------------------------------|------------|
| *Neoechinorhynchus buttnerae* | *Mentha piperita, Lippia alba, and Zingiber officinale* | 360, 540, 720, 1440, and 2880 mg/L | ➢ 1 h 20 min–1 h 55 min/540–2880 mg/L of *M. piperita* | 100% anthelmintic | Costa, et al. [73] |
|                     |               |                | ➢ 1 h 55 min/2880 mg/L of *L. alba* | 100% anthelmintic | |
|                     |               |                | ➢ 2 h 50 min/2880 mg/L of *Z. officinale* | 100% anthelmintic | |
| *Neoechinorhynchus buttnerae* | *Piper hispidinervum,* *Piper hispidum, Piper marginatum,* and *Piper callosum* | 0.19, 0.39, 0.78, 1.56, 3.125, 6.25, 12.5, 25, and 50 mg/L | ➢ 15 min/0.78 mg/L of *P. hispidinervum* | 100% anthelmintic | dos Santos, et al. [74] |
|                     |               |                | ➢ 2 h/50 mg/L of *P. hispidum* | 100% anthelmintic | |
|                     |               |                | ➢ 2 h/12.5 mg/L of *P. marginatum* | 100% anthelmintic | |
|                     |               |                | ➢ 2 h/25 mg/L of *P. callosum* | 100% anthelmintic | |
| *Anacanthorus spathulatus,* *Notozothecium janauachensis,* and *Mymarothecium boegeri* | *Cymbopogon citratus* | 100, 200, 300, 400, and 500 mg/L | ➢ 10 min/400 mg/L/100% anthelmintic | Gonzalez, et al. [10] |
| *A. spathulatus,* *N. janauachensis,* and *M. boegeri* | *Pterodon emarginatus* | 0, 50, 100, 200, 400, and 600 mg/L | ➢ 15 min/400 and 600 mg/L | 100% anthelmintic | Valentim, et al. [25] |
| *A. spathulatus,* *N. janauachensis,* and *M. boegeri* | *Lippia origanoides* | 10, 20, 40, 80, 160, and 320 mg/L | ➢ 30 min/320 and 160 mg/L | 100% anthelmintic | Soares, et al. [78] |
| *A. spathulatus,* *N. janauachensis,* and *M. boegeri* | *L. alba* | 160, 320, 640, 1280, and 2560 mg/L | ➢ 20 min/1280 and 2560 mg/L | 100% anthelmintic | Soares, et al. [77] |
| *Dactylogyrus minutus* and *Dactylogyrus extensus* | *L. alba, L. Origanoides,* and *L. sidoides* | 160 and 320 mg/L | ➢ 5 min/100 mg/L of *L. origanoides* and *L. sidoides* | 100% anthelmintic | Brasil, et al. [9] |
| *Cichlidogyrus tilapiae* | *Ocimum gratissimum* | 40, 160, and 320 mg/L | ➢ 2 h/320 mg/L | 100% anthelmintic | Meneses, et al. [95] |
| *Cichlidogyrus tilapiae,* *Cichlidogyrus thorsonae,* *Cichlidogyrus hallii,* and *Scutogyrus longicornis* | *L. sidoides* and *Mentha piperita* | 160 and 320 mg/L | ➢ 1 min and 58 s/160 mg/L of *L. sidoides* | 100% anthelmintic | de Oliveira Hashimoto, et al. [82] |
| Parasitic Pathogens                        | Essential Oil                        | Concentrations | Elimination Time/Effectiveness Concentration/Elimination Percentage                                                                 | References |
|-------------------------------------------|--------------------------------------|----------------|---------------------------------------------------------------------------------------------------------------------------------------|------------|
| *Dawestrema cycloancistrium* and *Dawestrema cycloancistrioides* | *M. piperita*                         | 80, 160, and 320 mg/L | ➢ 30 min/160 and 320 mg/L/100% anthelmintic                                                                                           | Malheiros, et al. [85] |
| *Gyrodactylus* sp.                        | *Hesperozygis ringens* and *Ocimum gratissimum* | 20 and 40 mg/L of *H. ringens* and 5 and 10 mg/L of *O. gratissimum* | ➢ 1 h/10 mg/L of *O. gratissimum*/50% anthelmintic ➢ 1 h/40 mg/L of *H. ringens*/40% anthelmintic | Bandeira, et al. [37] |
| *Gyrodactylus* sp.                        | *Ocimum americanum*                   | 10 and 50 mg/L    | ➢ 1 h/50 mg/L/98% anthelmintic                                                                                                     | Sutili, et al. [86] |
| *Ichthyophthirius multifiliis* trophonts and tomonts | *Varronia curassavica* *(VCUR-001 VCUR-202 VCUR-509 VCUR-601)* | 10, 25, 50, 75, 100, and 200 mg/L | ➢ 1 h/10 mg/L of *V. curassavica*, VCUR-202/100% antiparasitic for *Trophont* ➢ 1 h/50 mg/L of *V. curassavica*, VCUR-202/100% antiparasitic for *Tomont* | de Castro Nizio, et al. [35] |
| *Ichthyophthirius multifiliis*            | *Hyptis mutabilis*                    | 10 and 20 mg/L    | ➢ 30 min/10 mg/L/100% antiparasitic                                                                                                | Da Cunha, et al. [91] |
| *Ichthyophthirius multifiliis* trophonts  | *Melaleuca alternifolia*, *Lavandula angustifolia*, and *Mentha piperita* | 57, 114, 227, and 455 µL/L | ➢ 1 h/455 µL/L/100% antiparasitic                                                                                                  | Valladão, et al. [92] |
| *Euclinostomum heterostomum*              | *Verbesina alternifolia* and *Mentha piperita* | 200 to 1000 mg/L  | ➢ 24 h/600 mg/L of *V. alternifolia*/100% anthelmintic ➢ 24 h/1000 mg/L of *M. Piperita*/50% anthelmintic                         | Mahdy, et al. [90] |
| *Hexamita inflata*                        | *L. angustifolia* and *L. × intermedia Miss Donnington* | 1, 0.5, or 0.1% | ➢ 30 min/1 and 0.5%/100% antiparasitic                                                                                                | Moon, et al. [87] |
4. Essential Oils as Antibacterial Agents: An In Vitro Perspective

4.1. Aeromonas spp.

*Aeromonas salmonicida* has been known as the causative agent of furunculosis [94]. *Aeromonas hydrophila, Aeromonas sobria,* and *Aeromonas veronii* are among the most common bacteria that cause motile *Aeromonas septicemia* in fish [94,95]. In addition, it is known that many different *Aeromonas* species cause disease in fish.

The antimicrobial effects of essential oils of some herbs on *Aeromonas salmonicida* subsp. *Salmonicida* has been investigated (Table 3). Hayatgheib, et al. [96] found that MIC and MBC values of essential oils (EOs) of different herbs on different *A. salmonicida* subsp. *Salmonicida* isolates were in the range of 113 to ≥3628 µg/mL, and the most effective (MIC and MBC: ≤520 µg/mL) herb species were *Cinnamomum zeylanicum*/*verum, Origanum vulgare, Origanum compactum,* and *Origanum heracleoticum,* *Eugenia caryophyllata,* and *Thymol rich Thyme vulgaris.*

In a different study, the antimicrobial effects of *Origanum onites, O. vulgare,* and *Thymbra spicata* EOs on 18 different *A. salmonicida* isolates, and it was reported that EOs of these herbs formed 10 to 30 mm zone depending on the disc diffusion test, and they had moderate inhibitory depending on MIC values (800 µg/mL) [97]. Among *Thymus vulgaris, Laurus nobilis, Rosmarinus officinalis,* *Petroselinum crispum,* and *Thymus vulgaris* EOs showed the highest zone diameter with 30 mm on *A. salmonicida* [98], while *Azadirachta indica* nanoemulsion also exhibited similar results [99]. *Cinnamomum cassia* EO was reported to have a very high inhibitory effect on *A. salmonicida* subsp. with a 56 mm zone diameter [100].

Tural, et al. [98] reported that among *T. vulgaris, L. nobilis,* and *R. officinalis,* and *P. crispum* EOs, *T. vulgaris* EO had the highest zone diameter on *Aeromonas sobria* and *Aeromonas veronii* with 31.5 mm and 36 mm, respectively. It was determined that *Origanum acutidens* EO formed a zone diameter of 32.7 mm on *Aeromonas hydrophila* [101].

*Cymbopogon nardus* [102] and *Syzygium aromaticum* [103] EOs had a strong inhibitory effect on *Aeromonas hydrophila* (ATCC 49140) and *Aeromonas spp.* with MIC values of 0.488–0.977 µg/mL and 0.015–0.031 µg/mL, respectively. It was found that *C. cassia, Cinnamomum aromaticum,* *Cymbopogon citratus,* and *Origanum vulgare* EOs were effective against *Aeromonas spp.,* *Aeromonas salmonicida* subsp. *Salmonicida,* *A. hydrophila,* and *A. veronii* bv. *Sobria* (Mean Percent MBC: 0.02% to 0.65%) [100]. It was reported that *Mentha arvensis* and *Mentha piperita* EOs generally exhibited weak inhibitory effects on 12 different *Aeromonas* spp. Isolates (MIC > 1840 µg/mL) while *M. arvensis* EO shows moderate inhibitory (MIC: 1250 µg/mL) on only one isolate [36].

Majolo, et al. [104] investigated the antimicrobial effects of *Lippia alba, Lippia origanoides,* and *Lippia sidooides* EOs on *Aeromonas hydrophila* and found only the moderate inhibitory (MIC and MBC: 1250 µg/mL) effect of *L. sidooides* EO.

Among *Piper aduncum, Piper callosum,* and *Piper hispidinervum* EOs on 11 different *A. hydrophila* isolates, only *P. marginatum* had a strong inhibitory effect (MIC: 468.8 and 234.4 µg/mL) on three different *A. hydrophila* isolates [43].

*Ocimum gratissimum* and *Hesperozygis ringens* EOs showed a marked activity (MIC and MBC: 400 µg/mL) on *A. hydrophila,* which is among the pathogens of *Aeromonas hydrophila* and *Aeromonas veronii* (MIC and MBC: 400 µg/mL) while they exhibited a moderate inhibitory (≥800 µg/mL) on *A. veronii* [37].

A strong inhibitory effect of *Hieraca livaria* EO with 3 µL/mL and 9 µL/mL MIC values was reported on *A. hydrophila* and *A. veronii,* respectively [105]. Among nine different herb EOs, *Conoea scopariaeides* and *Lippia origanoides* EOs had remarkable activity against *A. hydrophila* with the low respective MIC and MBC values of 200 µg/mL [106].

It was reported that *Eucalyptus globulus,* *Lavendula angustifolia,* *Origanum vulgare,* and *Melaleuca alternifolia* nanoemulsions were more effective on *A. hydrophila* than their EOs, and among four different herbs, *O. vulgare* essential oil was found as the most effective with 25 µg/mL MIC and MBC, and the nano-emulsion was also found as the most effective with 3.12 µg/mL MIC and 12.5 µg/mL MBC [51]. However, generally moderate and weak inhibitory effects of *Ocimum americanum* [86], *Hesperozygis ringens* and *Ocimum*
gratissimum [107], and Lippia alba [108] EOs on different A. hydrophila isolates were also reported.

4.2. Vibrio spp., Listonella anguillarum, and Photobacterium damselae

Historically, vibriaceae family members are the most severe infectious diseases in marine fish species [109]. The antimicrobial effects of O. vulgare, M. alternifolia, C. citratus, C. verum, and T. vulgaris EOs on Vibrio campbellii, Vibrio harveyi, Vibrio vulnificus, and Vibrio parahaemolyticus have been researched, and it was reported that generally moderate and weak inhibitory effects of these EOs on Vibrio spp [110]. Wei and Wee [102] indicated that Cymbopogon nardus EO showed potent inhibitory effects with 0.244 µg/mL and 0.488 µg/mL MIC values on Vibrio spp. and Vibrio damsela, respectively. Similarly, a strong inhibitory effect of Thymus vulgaris EO was reported, respectively, with 320 µg/mL MIC for Vibrio ordalii and Vibrio anguillarum and 80 µg/mL MIC for Vibrio parahaemolyticus [111]. A marked activity of Syzygium aromaticum EO with 0.015 µg/mL MIC values was reported on six different isolates of Vibrio spp. [103].

O. vulgare subsp. Hirtum, O. onites, and O. marjorana EOs had weak or moderate inhibitory effects on Vibrio splendidus, Vibrio alginolyticus, and Listonella anguillarum with zone diameter of 7.3 to 14.3 mm, 7.8 to 13.6 mm, and 9.1 to 14.1 mm, respectively [112]. It was reported that Argania spinosa EO had marked activity with 62.5 µL/mL MIC value on L. Anguillarum [113].

It was reported that E. globulus, L. angustifolia, O. vulgare, and M. alternifolia nanoemulsions were more effective on Photobacterium damselae than their EOs, and among these herbs, O. vulgare EO and nano-emulsion were found as the most effective [51].

4.3. Pseudomonas fluorescens

Pseudomonas fluorescens is a harmful pathogen in a variety of farmed fish. It was reported that Ocimum basilicum EO exhibited a potent inhibitory with 9 µL/mL MIC value on P. fluorescens [105]. C. Nardus [102] and S. aromaticum [103] EOs showed marked activity on Pseudomonas spp. and P. Aeruginosa. Thymus vulgaris EO had a moderate inhibitory effect on Pseudomonas sp. with 640 µg/mL MIC value [111].

Among T. vulgaris, L. nobilis, R. officinalis, and P. crispum EOs, T. vulgaris EO exhibited the highest zone diameter with 26.5 mm on P. fluorescens [98]. T. vulgaris was also found as the most effective with a 13 mm zone diameter on P. Aeruginosa [114].

4.4. Citrobacter spp.

Citrobacter spp. is an opportunistic fish pathogen affecting farmed fish species. Bandeira, et al. [37] reported that O. gratissimum and H. ringens EOs showed a moderate or weak inhibitory (MIC and MBC: >1600 µg/mL) on Citrobacter freundii. Among Achyrocline satureioides, Aniba parviflora, Aniba rosaeodora, Anthemis nobilis, Conobea scoparioides, Cupressus sempervirens, Illicium verum, Lippia origanoides, and Melaleuca alternifolia EOs on C. freundii, only L. origanoides EO exhibited a moderate inhibitory [43].

It was determined that C. freundii showed susceptibility towards the Argania spinosa EO with a zone diameter of 15 mm [113], and C. nardus EO with a MIC value of 0.244 µg/mL [102].

4.5. Raoultella ornithinolytica

Raoultella ornithinolytica was isolated from kidneys and skin lesions of naturally diseased silver catfish (Rhamdia quelen), and Ocimum gratissimum EO showed a moderate inhibitory effect on this pathogen [37].

4.6. Nocardia seriolae

Nocardia seriolae is the causative agent of nocardiosis in cultured fish species [115]. Ismail and Yoshida [116] reported that MIC values of C. Zeylanicum, Thymus vulgaris, Cymbopogon flexuosus, and Melaleuca alternifolia EOs on 80 Nocardia seriolae isolates were in
the range of 5 to $>5120 \, \mu g/mL$, and the most effective herb species were *C. zeylanicum* and *T. vulgaris* with MICs 5–160 $\mu g/mL$, respectively.

4.7. *Flavobacterium* spp.

*Flavobacterium* species are widespread in soil habitats and fresh and marine waters and cause economic losses in cultured fish. *T. vulgaris* EO exhibited a potent inhibitory with 320 $\mu g/mL$ MIC value on *F. psychrophilum* [111].

Previous studies have reported that *Flavobacterium* spp. showed high susceptibility towards the *S. aromaticum* EO with a MIC value of 0.031 $\mu g/mL$ [103], and *C. nardus* EO with a MIC value of 0.977 $\mu g/mL$ [102]. *R. officinalis* EO showed a moderate zone diameter with $>18 \, mm$ on *F. psychrophilum* [117]. A remarkable activity of *Allium tuberosum* EO with 20 $\mu g/mL$ to 80 $\mu g/mL$ MIC values was reported on six different isolates of *Flavobacterium columnare* [118].

4.8. *Staphylococcus aureus*

*Staphylococcus aureus* is an important Gram-positive opportunistic pathogen for aquaculture species. Gulec, et al. [101] reported that *O. acutidens* EO formed a zone diameter of 28 mm on *S. aureus*, *Z. officinale*, *N. Sativa*, *T. Vulgaris*, *S. Aromaticum* and *E. Sativa* EOs had no inhibitory effects on *S. aureus* [114].

4.9. *Streptococcus* spp., *Lactococcus* spp., and *Vagococcus salmoninarum*

*Streptococcaceae* family species are important Gram-positive pathogens for cultured fish. Among *L. alba*, *L. sidoides*, *M. piperita*, *O. gratissimum*, and *Z. officinale* EOs, strong inhibitory effects of *L. sidoides* EO was reported on *Streptococcus agalactiae* with 312.5 $\mu g/mL$ MIC and 416.7 $\mu g/mL$ MBC values [119]. It was determined that *S. agalactiae* had high susceptibility towards the *O. Basilicum* [105], *M. piperita* [45], *C. Nardus* [102], and *S. Aromaticum* [103] with MIC value of 9 $\mu g/mL$, 0.125 mg/mL, 0.244 $\mu g/mL$, and 0.015 $\mu g/mL$, respectively.

Gholipourkanani, et al. [51] determined that among *E. globulus*, *L. angustifolia*, *O. vulgare*, and *M. alternifolia* nano-emulsions and EOs, *O. vulgare* EO and/or nano-emulsion were found as the most effective on *Streptococcus iniae*. *Oliveria decumbens* EO had a zone of inhibition of 69 mm, and MIC and MBC values of 0.5 mg/mL and 2 mg/mL, respectively, on *S. iniae* [120].

A remarkable activity of *Z. multiflora* and *R. officinalis* EOs were reported, respectively, with 0.06 $\mu L/mL$ and 0.5 $\mu L/mL$ MIC, and 0.12 $\mu L/mL$ and 0.25 $\mu L/mL$ MBC for *S. iniae* [121]. Similarly, *R. officinalis*, *Z. Multiflora*, *A. Graveolens*, and *E. Globulus* EOs exhibited potent inhibitory effects on *S. iniae*, and *R. officinalis* showed the highest inhibition with a zone of 45 mm, and MIC value of 3.9 $\mu g/mL$, and MBC value of 7.8 $\mu g/mL$ [122].

*Cinnamomum verum*, *Citrus hystrix*, *Cymbopogon citratus*, and *Curcuma longa* EOs had marked activity against *S. iniae* with the low respective MIC values of 40, 160, 320, and 160, respectively [123]. Pirbalouti, et al. [124] determined that *Thymus daenensis* and *Myrtus communis* EOs formed a zone diameter of 19 mm and 15.67 mm, respectively, on *S. iniae*.

It was reported that *Streptococcus* spp. showed high susceptibility towards the *S. aromaticum* EO with a MIC value of 0.062 [103] and *C. nardus* EO with a MIC value of 0.488 [102].

*Zataria multiflora*, *Thymbra spicata*, *Bunium persicum*, *Satureja bachtiarica*, and *Thymus daenensis* EOs exhibited potent inhibitory effects with MIC and MBC values ranged from 4 $\mu L/mL$ to 16 $\mu L/mL$ against the *L. garvieae* [125]. *Zataria multiflora*, *Cinnamomum zeylanicum*, and *Allium sativum* EOs showed a potent inhibitory (MIC: 0.12 to 0.5 $\mu L/mL$ and MBC: 0.12 to 1 $\mu L/mL$) on *L. Garvieae* [126]. It was determined that *Argania spinosa* EO with a zone diameter of ~11 mm and MIC values of 125 $\mu L/mL$ on *L. Garvieae* [113].

*Thymus vulgaris* EO had marked activity with a zone diameter of 36.7 mm on *L. Garvieae* [101]. Among *T. vulgaris*, *L. nobilis*, *R. officinalis*, and *P. crispum* EOs, *T. vulgaris* EO exhibited the highest zone diameter with 29.5 mm on *L. Garvieae* [98].
It was found that *T. vulgaris* EO was more effective on *Lactococcus piscium* (MIC: 320 µg/mL) than *Lactococcus lactis* (MIC: 1280) and *Lactococcus lactis* subsp. *lactis* bv. *diacetylactis* (MIC: 1280) [111].

Among *Origanum vulgare, Hypericum perforatum, Rosmarinus officinalis, Zingiber officinalis, Eugenia caryophyllata, Mentha piperita, Lavandula hybrid*, and *Nigella sativa* EOs, *O. vulgare* and *E. caryophyllata* EOs showed remarkable activity against *Vagococcus salmoninarum* with the low respective MIC values of 125 µL/mL and 250 µL/mL, respectively [42].
Table 3. Essential oils as antibacterial agents: an in vitro perspective.

| Bacterial Pathogens                  | Essential Oil       | Concentrations       | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|--------------------------------------|---------------------|----------------------|-------------------------------------------------------------|------------|
| *Aeromonas salmonicida* subsp. *salmonicida* ATCC 14174 | Cinnamomum zeylanicum/verum | 61 to 3628 µg/mL     | ➢ C. zeylanicum/verum MIC and MBC: 245                     | Hayatgheib, et al. [96] |
|                                      | Origanum vulgare    |                      | ➢ O. vulgare MIC and MBC: 226                              |            |
|                                      | Origanum compactum  |                      | ➢ O. compactum MIC and MBC: 458                             |            |
|                                      | Origanum heracleoticum |                  | ➢ O. heracleoticum MIC and MBC: 458                        |            |
|                                      | Eugenia caryophyllata |                   | ➢ E. caryophyllata MIC and MBC: 520                        |            |
|                                      | Geraniol rich Thymus vulgaris |                  |                                                             |            |
|                                      | Thymol rich Thymus vulgaris |                  |                                                             |            |
|                                      | *Thymus* saturoides  |                      |                                                             |            |
|                                      | Thujanol rich *Thymus* vulgaris |                |                                                             |            |
|                                      | *Melaleuca* alternifolia |                 |                                                             |            |
|                                      | Cinnamomum camphora  |                      |                                                             |            |
|                                      | Linalool rich *Thyme* vulgaris |            |                                                             |            |
|                                      | *Rosemary* officinalis |                    |                                                             |            |
|                                      | Cinnamomum camphora  |                      |                                                             |            |
|                                      | Linalool rich *Thyme* vulgaris |          |                                                             |            |
|                                      | *Rosemary* officinalis |                   |                                                             |            |
|                                      | Cinnamomum camphora  |                      |                                                             |            |
|                                      | Linalool rich *Thyme* vulgaris |          |                                                             |            |
|                                      | *Rosemary* officinalis |                   |                                                             |            |
|                                      | Cinnamomum camphora  |                      |                                                             |            |
|                                      | Linalool rich *Thyme* vulgaris |          |                                                             |            |
|                                      | *Rosemary* officinalis |                   |                                                             |            |

| *A. salmonicida* subsp. *salmonicida* CAE 235 | C. zeylanicum/verum | 61 to 3628 µg/mL     | ➢ C. zeylanicum/verum MIC and MBC: 245                     | Hayatgheib, et al. [96] |
|                                              | O. vulgare          |                      | ➢ O. vulgare MIC and MBC: 226                              |            |
|                                              | O. compactum        |                      | ➢ O. compactum MIC and MBC: 458                             |            |
|                                              | O. heracleoticum    |                      | ➢ O. heracleoticum MIC and MBC: 458                        |            |
|                                              | E. caryophyllata    |                      | ➢ E. caryophyllata MIC and MBC: 520                        |            |
|                                              | Geraniol rich *T. vulgaris* |                |                                                             |            |
|                                              | Thymol rich *T. vulgaris* |                  |                                                             |            |
|                                              | *T. saturoides*      |                      |                                                             |            |
|                                              | Thujanol rich *T. vulgaris* |                |                                                             |            |
|                                              | *M. alternifolia*    |                      |                                                             |            |
|                                              | *C. camphora*        |                      |                                                             |            |
|                                              | Linalool rich *T. vulgaris* |            |                                                             |            |
|                                              | *R. officinalis*     |                      |                                                             |            |
Table 3. Cont.

| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|-------------------------------------------------------------|------------|
| *A. salmonicida* subsp. *salmonicida* CAE 452 | C. zeylanicum/verum | 61 to 3628 µg/mL | C. zeylanicum/verum MIC and MBC: 61 | Hayatgheib, et al. [96] |
|                     | O. vulgare    |                | O. vulgare MIC and MBC: 113                                |            |
|                     | O. compactum  |                | O. compactum MIC and MBC: 229                              |            |
|                     | O. heracleoticum |            | O. heracleoticum MIC and MBC: 458                          |            |
|                     | E. caryophyllata |            | E. caryophyllata MIC and MBC: 520                          |            |
|                     | Geraniol rich T. vulgaris |        | Thymol rich T. vulgaris MIC and MBC: 440                   |            |
|                     | T. satureoides |                | Thujanol rich T. vulgaris                                 |            |
|                     | M. alternifolia |               |                                                             |            |
|                     | C. camphora   |                |                                                             |            |
|                     | Linalool rich T. vulgaris |         |                                                             |            |
|                     | R. officinalis |                |                                                             |            |

| A. salmonicida subsp. *salmonicida* CAE 258 | C. zeylanicum/verum | 61 to 3628 µg/mL | C. zeylanicum/verum MIC and MBC: 490 | Hayatgheib, et al. [96] |
|-------------------------------------------|-------------------|----------------|-------------------------------------|------------------------|
|                                           | O. vulgare        |                | O. vulgare MIC and MBC: 453         |                        |
|                                           | O. compactum      |                | O. compactum MIC and MBC: 458        |                        |
|                                           | O. heracleoticum  |                | O. heracleoticum MIC and MBC: 458    |                        |
|                                           | E. caryophyllata  |                | E. caryophyllata MIC and MBC: 916    |                        |
|                                           | Geraniol rich T. vulgaris |     | Thymol rich T. vulgaris MIC and MBC: 440 |                        |
|                                           | Thymol rich T. vulgaris |          | T. satureoides                      |                        |
|                                           | T. satureoides    |                | M. alternifolia                     |                        |
|                                           | C. camphora       |                | C. camphora                         |                        |
|                                           | Linalool rich T. vulgaris |       | Linalool rich T. vulgaris            |                        |
|                                           | R. officinalis    |                | R. officinalis                       |                        |
| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|--------------------|---------------|----------------|-------------------------------------------------------------|------------|
| *Vibrio campbellii* | ➢ O. vulgare  
➢ M. alternifolia  
➢ C. citratus  
➢ C. verum  
➢ T. vulgaris | 50 to 3000 µg/mL | ➢ O. vulgare MIC and MBC: 800  
➢ M. alternifolia MIC: 800 and MBC: 900  
➢ C. citratus MIC and MBC: 1500  
➢ C. verum MIC: 1000 and MBC: 1200  
➢ T. vulgaris MIC: 1900 and MBC: 2000 | Domínguez-Borbor, et al. [110] |
| *Vibrio harveyi* | ➢ O. vulgare  
➢ M. alternifolia  
➢ C. citratus  
➢ Cinnamomum verum  
➢ Thymus vulgaris | 50 to 3000 µg/mL | ➢ O. vulgare MIC: 700 and MBC: 800  
➢ M. alternifolia MIC and MBC: 800  
➢ C. citratus MIC: 1000 and MBC: 1100  
➢ C. verum MIC and MBC: 900  
➢ T. vulgaris MIC: 2000 and MBC: 2100 | Domínguez-Borbor, et al. [110] |
| *Vibrio vulnificus* | ➢ O. vulgare  
➢ M. alternifolia  
➢ C. citratus  
➢ C. verum  
➢ T. vulgaris | 50 to 3000 µg/mL | ➢ O. vulgare MIC: 900 and MBC: 1100  
➢ M. alternifolia MIC: 1000 and MBC: 1200  
➢ C. citratus MIC: 2000 and MBC: 2200  
➢ C. verum MIC: 1000 and MBC: 1100  
➢ T. vulgaris MIC and MBC: 1800 | Domínguez-Borbor, et al. [110] |
| *Vibrio parahaemolyticus* | ➢ O. vulgare  
➢ M. alternifolia  
➢ C. citratus  
➢ C. verum  
➢ T. vulgaris | 50 to 3000 µg/mL | ➢ O. vulgare MIC: 800 and MBC: 900  
➢ M. alternifolia MIC: 600 and MBC: 900  
➢ C. citratus MIC: 1400 and MBC: 1500  
➢ C. verum MIC: 1500 and MBC: 1600  
➢ T. vulgaris MIC and MBC: 1500 | Domínguez-Borbor, et al. [110] |
### Table 3. Cont.

| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|-------------------------------------------------------------|------------|
| **Vagococcus salmoninarum** | Origanum vulgare | 0.195 to 25 final well concentration for agar diffusion assay, 1000–0.01 µL/mL/well and MIC 250 | O. vulgare 17 to 20.33 mm/1.56 to 25 µL/mL/well and MIC: 125 | Metin and Biçer [42] |
| | Hypericum perforatum | | R. officinalis MIC: 1000 | |
| | Rosmarinus officinalis | | Z. officinale MIC: 500 | |
| | Zingiber officinale | | E. caryophyllata 17.83–18.66 mm/12.5–25 µL/mL/well and MIC 250 | |
| | Mentha piperita | | M. piperita MIC: 500 | |
| | Lavandula hybrida | | L. hybrid MIC: 1000 | |
| | Nigella sativa | | N. sativa MIC: >1000 | |
| **Aeromonas spp. isolates (248, 249, 284, 351, 432, 520, 533, 561, 562, 565, 568 and 570)** | Mentha arvensis | 312.5 to 40,000 µg/mL | M. arvensis MIC and MBC 1250 (isolate 520) | Chagas, et al. [36] |
| | Mentha piperita | | M. piperita MIC and MBC 2500 (isolate 570) | |
| | Other isolates | | Other isolates MIC: >145 | |
| **Aeromonas hydrophila isolates (248, 249, 284, 432, 520, 533, 562, 568, 569 and 570)** | Piper aduncum | 117.2 to 30,000 µg/mL | P. marginatum MIC: 468.8 for A. hydrophila (248 and 570) | Majolo, et al. [43] |
| | Piper callosum | | P. marginatum MIC: 234.4 for A. hydrophila (569) | |
| | Piper hispidinervum | | Others MIC: >937.5 | |
| | Piper hispidum | | | |
| | Piper marginatum | | | |
| **Streptococcus agalactiae** | Lippia alba | 312 to 20,000 µg/mL | L. alba MIC and MBC: 1666.7 | Majolo, et al. [119] |
| | Lippia sidoides | | L. sidoides MIC: 312.5 and MBC: 416.7 | |
| | Mentha piperita | | M. piperita MIC and MBC: 1250 | |
| | Ocimum gratissimum | | O. gratissimum MIC and MBC: 2500 | |
| | Zingiber officinale | | Z. officinale MIC:625 and MBC: 833.3 | |
### Table 3. Cont.

| Bacterial Pathogens                        | Essential Oil       | Concentrations          | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen                                                                 | References         |
|--------------------------------------------|---------------------|-------------------------|----------------------------------------------------------------------------------------------------------------------------|---------------------|
| Aeromonas hydrophila                       | Lippia alba         | 625 to 20,000 µg/mL     | L. alba MIC and MBC: 5000                                                                                                   | Majolo, et al. [104]|
|                                            | Lippia origanoides  |                         | L. origanoides MIC and MBC: 2500                                                                                             |                     |
|                                            | Lippia sidoides     |                         | L. sidoides MIC and MBC: 1250                                                                                               |                     |
| Aeromonas veronii                          | Ocimum gratissimum  | 100 to 3200 µg/mL       | 400 (MIC and MBC) for Rifampicin resistant A. hydrophila and A. veronii                                                                 | Bandeira, et al. [37]|
| Aeromonas hydrophila                       |                     |                         | 800 (MIC) and 1600 (MBC) for A. hydrophila and A. veronii                                                                 |                     |
| Citrobacter freundii                       |                     |                         | 1600 (MIC) and MBC for C. freundii                                                                                          |                     |
| Raoultella ornithinolytica                 |                     |                         | 3200 (MIC and MBC) for R. ornithinolytica                                                                                   |                     |
|                                            | Hesperozygis ringens |                         | 800 (MIC and MBC) for A. veronii                                                                                           |                     |
|                                            | Achyrocline satureioides |                     | satureioides MIC and MBC: >6400                                                                                           |                     |
|                                            | Aniba parviflora    |                         | parviflora MIC: 800 and MBC: 1600                                                                                            |                     |
|                                            | Aniba rosaeodora    |                         | rosaeodora MIC and MBC: 3200                                                                                                |                     |
|                                            | Anthemis nobilis    |                         | nobilis MIC and MBC: 6400                                                                                                  |                     |
|                                            | Conobea scoparioides|                         | scoparioides MIC and MBC: 200                                                                                                |                     |
|                                            | Cupressus sempervirens |                     | sempervirens MIC and MBC: >6400                                                                                           |                     |
|                                            | Illicium verum      |                         | verum MIC: 1600 and MBC: 3200                                                                                                |                     |
|                                            | Lippia origanoides  |                         | L. origanoides MIC and MBC: 200                                                                                             |                     |
|                                            | Melaleuca alternifolia |                     | M. alternifolia MIC: 3200 and MBC: 6400                                                                                     |                     |
Table 3. Cont.

| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|---------------------------------------------------------------|------------|
| C. freundii         | satureioides  | 12.5 to 6400 µg/mL | satureioides MIC and MBC: >6400                             | Bandeira Jr, et al. [106] |
|                     | parviflora    |                | parviflora MIC: 3200 and MBC: 6400                         |            |
|                     | roseaodora    |                | roseaodora MIC and MBC: 3200                                |            |
|                     | nobilis       |                | nobilis MIC and MBC: >6400                                 |            |
|                     | scoparioides  |                | scoparioides MIC and MBC: 3200                              |            |
|                     | sempervirens  |                | sempervirens MIC and MBC: >6400                            |            |
|                     | verum         |                | verum MIC and MBC: >6400                                   |            |
|                     | L. origanoides|                | L. origanoides MIC and MBC: 800                             |            |
|                     | M. alternifolia|              | M. alternifolia MIC and MBC: >6400                         |            |
| R. ornithinolytica  | satureioides  | 12.5 to 6400 µg/mL | satureioides MIC and MBC: >6400                             | Bandeira Jr, et al. [106] |
|                     | parviflora    |                | parviflora MIC and MBC: 3200                                |            |
|                     | roseaodora    |                | roseaodora MIC and MBC: 3200                                |            |
|                     | nobilis       |                | nobilis MIC and MBC: >6400                                 |            |
|                     | scoparioides  |                | scoparioides MIC and MBC: 3200                              |            |
|                     | sempervirens  |                | sempervirens MIC and MBC: >6400                            |            |
|                     | verum         |                | verum MIC and MBC: >6400                                   |            |
|                     | L. origanoides|                | L. origanoides MIC and MBC: 800                             |            |
|                     | M. alternifolia|              | M. alternifolia MIC: 6400 and MBC > 6400                   |            |
| Aeromonas hydrophila, Aeromonas veronii, Pseudomonas fluorescens, and Streptococcus agalactiae | Ocimum basilicum | 3 and 6 µL/disc, 3 to 300 µL/mL MIC | 13.5 mm/3 µL/disc and MIC: 3 for Aeromonas hydrophila | El-Ekiaby [105] |
| Bacterial Pathogens       | Essential Oil       | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen                                                                 | References                        |
|---------------------------|---------------------|----------------|----------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| *Streptococcus agalactiae* | *Mentha piperita*   | -              | ➢ MIC: 0.125 mg/mL.                                                                                                          | de Souza Silva, et al. [45]       |
| *Photobacterium damsela*  | *Eucalyptus globulus* | -              | ➢ *E. globulus* MIC: 25 and MBC: 50 ➢ Nano-emulsions from *E. globulus* MIC: 12.5 and MBC: 25 ➢ *L. angustifolia* MIC: 100 and MBC: 50 ➢ Nano-emulsions from *L. angustifolia* MIC: 50 and MBC: 50 ➢ *O. vulgare* MIC: 25 and MBC: 25 ➢ Nano-emulsions from *O. vulgare* MIC: 3.12 and MBC: 12.5 ➢ *M. alternifolia* MIC: 100 and MBC: 100 ➢ Nano-emulsions from *M. alternifolia* MIC: 50 and MBC: 50 | Gholipourkanani, et al. [51]     |
| *Aeromonas hydrophila*    | *E. globulus*       | -              | ➢ *E. globulus* MIC: 100 and MBC: 100 ➢ Nano-emulsions from *E. globulus* MIC: 50 and MBC: 50 ➢ *L. angustifolia* MIC: 100 and MBC: 100 ➢ Nano-emulsions from *L. angustifolia* MIC: 50 and MBC: 50 ➢ *O. vulgare* MIC: 25 and MBC: 25 ➢ Nano-emulsions from *O. vulgare* MIC: 3.12 and MBC: 12.5 ➢ *M. alternifolia* MIC: 50 and MBC: 50 ➢ Nano-emulsions from *M. alternifolia* MIC: 12.5 and MBC: 50 | Gholipourkanani, et al. [51]     |
### Table 3. Cont.

| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|-------------------------------------------------------------|------------|
| *Streptococcus iniae* | E. globulus, L. angustifolia, O. vulgare, M. alternifolia | - | ➢ E. globulus MIC: 100 and MBC: 100  
➢ Nano-emulsions from E. globulus MIC: 100 and MBC: 100  
➢ L. angustifolia MIC: 100 and MBC: 100  
➢ Nano-emulsions from L. angustifolia MIC: 100 and MBC: 100  
➢ O. vulgare MIC: 25 and MBC: 25  
➢ Nano-emulsions from O. vulgare MIC: 3.12 and MBC: 12.5  
➢ M. alternifolia MIC: 100 and MBC: 100  
➢ Nano-emulsions from M. alternifolia MIC: 50 and MBC: 50 | Gholipourkanani, et al. [51] |
| *Yersinia ruckeri* (2 isolates) | Thymus vulgaris, Laurus nobilis, Rosmarinus officinalis, Petroselinum crispum | 15 µL/disc | ➢ T. vulgaris 31.50 and 29.5 mm  
➢ L. nobilis 11.5 mm  
➢ R. officinalis 10 mm and 10.5 mm  
➢ P. crispum 7 mm and 0 mm | Tural, et al. [98] |
| *Lactococcus garvieae* | T. vulgaris, L. nobilis, R. officinalis, P. crispum | 15 µL/disc | ➢ T. vulgaris 29.5 mm  
➢ L. nobilis 18.5 mm  
➢ R. officinalis 13 mm  
➢ P. crispum 6 mm | Tural, et al. [98] |
| *Pseudomonas fluorescens* | T. vulgaris, L. nobilis, R. officinalis, P. crispum | 15 µL/disc | ➢ T. vulgaris 26.5 mm  
➢ L. nobilis 9.5 mm  
➢ R. officinalis 10 mm  
➢ P. crispum 6.5 mm | Tural, et al. [98] |
### Table 3. Cont.

| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|-------------------------------------------------------------|------------|
| *Aeromonas sobria* | ➢ T. vulgaris  
➢ L. nobilis  
➢ R. officinalis  
➢ P. crispum | 15 µL/disc | ➢ T. vulgaris 31.5 mm  
➢ L. nobilis 15 mm  
➢ R. officinalis 17 mm  
➢ P. crispum 7 mm | Tural, et al. [98] |
| *Aeromonas salmonicida* | ➢ T. vulgaris  
➢ L. nobilis  
➢ R. officinalis  
➢ P. crispum | 15 µL/disc | ➢ T. vulgaris 30 mm  
➢ L. nobilis 13 mm  
➢ R. officinalis 14.5 mm  
➢ P. crispum 7.5 mm | Tural, et al. [98] |
| *Aeromonas veronii* | ➢ T. vulgaris  
➢ L. nobilis  
➢ R. officinalis  
➢ P. crispum | 15 µL/disc | ➢ T. vulgaris 36 mm  
➢ L. nobilis 18.5 mm  
➢ R. officinalis 17.5 mm  
➢ P. crispum 7 mm | Tural, et al. [98] |
| *Streptococcus iniae* | ➢ *Oliveria decumbens* | 15 mg/disc | ➢ 69 mm/disc and MIC: 0.5 mg/mL and MBC: 2 mg/mL | Vazirzadeh, et al. [120] |
| *Nocardia seriolae* (80 isolates) | ➢ *Cinnamomum zeylanicum*  
➢ *Thymus vulgaris*  
➢ *Cymbopogon flexuosus*  
➢ *Melaleuca alternifolia* | 5 to 5120 µg/mL | ➢ *C. zeylanicum* MIC: 5 to 160  
➢ *T. vulgaris* MIC: 10 to 160  
➢ *C. flexuosus* 20 to 640  
➢ *M. alternifolia* 160 to >5120 | Ismail and Yoshida [116] |
| *Aeromonas hydrophila* | ➢ *Ocimum americanum* | | ➢ MIC: 6400 | Sutili, et al. [86] |
### Table 3. Cont.

| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|------------------------------------------------------------|------------|
| Yersinia ruckeri, Aeromonas hydrophila, Listonella anguillarum, Edwarsiella tarda, Citrobacter freundii and Lactococcus garvieae | Argania spinosa | 0.5%, 1%, 2.5%, 5%, 7.5%, or 10% disc and 0.06 to 500 µL/ml MIC | ➤ 13–18.33 mm/7.5–10%/disc and MIC: 31.25 for Y. ruckeri <br> ➤ 14–17 mm/7.5–10%/disc and MIC: 62.5 for A. hydrophila <br> ➤ 12.33–17 mm/7.5–10%/disc and MIC: 62.5 for L. anguillarum <br> ➤ 14–17 mm/7.5–10%/disc and MIC: 125 for E. tarda <br> ➤ 10–9.66 mm/7.5–10%/disc and MIC: 62.5 for C. freundii <br> ➤ 11–11.33 mm/7.5–10%/disc and MIC: 125 for L. garvieae | Öntaş, et al. [113] |
| Aeromonas salmonicida subsp. salmonicida | Cinnamomum cassia <br> Cinnamomum zeylanicum <br> T. vulgaris <br> Syzygium aromaticum <br> Melaleuca alternifolia <br> Rosemarinus officinalis <br> Ocimum basilicum <br> C. citratus <br> Aniba rosacordora <br> Salvia officinalis <br> Lavendula angustifolia <br> O. vulgare | 25 µL of 20% solution/disc | ➤ C. cassia 56 mm <br> ➤ C. zeylanicum 27.3 mm <br> ➤ T. vulgaris 42 mm <br> ➤ S. aromaticum 29.3 mm <br> ➤ M. alternifolia 12.7 mm <br> ➤ R. officinalis 10.7 mm <br> ➤ O. basilicum 6.7 mm <br> ➤ C. citratus 44.7 mm <br> ➤ rosacordora 16.7 mm <br> ➤ S. officinalis 12.7 mm <br> ➤ L. angustifolia 12.7 mm <br> ➤ O. vulgare 46 mm | Starliper, et al. [100] |
| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|--------------|----------------|-------------------------------------------------------------|------------|
| *Aeromonas salmonicida* subsp. *salmonicida* (10 isolate) | C. cassia | Overall mean percent minimum bactericidal concentrations (MBC) | C. cassia (Lotus): 0.02% | Starliper, et al. [100] |
| *Aeromonas hydrophila* (5 isolate) | C. aromaticum, Cymbopogon citratus, Origanum vulgare, Thymus vulgaris | | C. cassia (Aromaland): 0.04% | |
| *Aeromonas veronii* bv. *sobria* (9 isolate) | *C. caviae* | | C. citratus (Stony Mountain Botanicals): 0.10% | |
| *Aeromonas popoffii* (17 isolate) | *C. veronii* bv. *sobria* (9 isolate) | | O. vulgare (Now Foods): 0.14% | |
| *Aeromonas allosaccharophila* (3 isolate) | *A. caviae* | | O. vulgare (Herbal Authority): 0.16% | |
| *Aeromonas encheleia* (9 isolate) | *A. popoffii* (17 isolate) | | O. vulgare (Stony Mountain Botanicals): 0.30% | |
| *Aeromonas mulluscorm* (4 isolate) | *A. allosaccharophila* (3 isolate) | | C. citratus (Now Foods): 0.36% | |
| *Aeromonas hydrophila* (14 isolates) | Hesperozygis ringens, Ocimum gratissimum | 100 to 3200 µg/mL | H. ringens MIC and MBC: 800 to 3200 µg/mL | Sutili, et al. [107] |
| *Lactococcus garvieae* | *Lippia alba* | the initial concentration of 176,100 µg/mL | MIC: 2862 | Sutili, et al. [108] |
| *Streptococcus iniae* (2 isolates) | Zataria multiflora, Rosmarinus officinalis | 1 to 0.0017 µL/mL | Z. multiflora MIC: 0.12 and MBC: 0.12 | Soltani, et al. [126] |
| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|-------------------------------------------------------------|------------|
| *Staphylococcus aureus*  <br> *Lactococcus garviae* <br> *Yersinia ruckeri*  <br> *Aeromonas hydrophila* | ➢ *Origanum acutidens* | 10 µL/disc | ➢ 28 mm for *S. aureus*  <br> ➢ 36.7 mm for *L. garviae*  <br> ➢ 28.7 mm for *Y. ruckeri*  <br> ➢ 32.7 mm for *A. hydrophila* | Gulec, et al. [101] |
| *Aeromonas salmonicida* | ➢ *Azadirachta indica* <br> (Nano-emulsion) | 40 µL/disc | ➢ 30 mm | Thomas, et al. [99] |
| *Staphylococcus aureus*  <br> *Pseudomonas aeruginosa* | ➢ *Z. officinale*  <br> ➢ *N. sativa*  <br> ➢ *T. vulgaris*  <br> ➢ *S. aromaticum*  <br> ➢ *E. sativa* | 10 µL/disc | ➢ *S. aromaticum* 4.5 mm for *S. aureus*  <br> ➢ *Z. officinale* 6.7 mm, *T. vulgaris* 13 mm,  <br> ➢ *S. aromaticum* 2 mm and *E. sativa* 10.3 mm for *P. aeruginosa* | Shehata, et al. [114] |
| *Edwardsiella* spp. (2 isolate)  <br> *Edwardsiella tarda* (18)  <br> *Vibrio* spp. (5 isolate)  <br> *Vibrio daniels*  <br> *Aeromonas* spp. (2 isolate)  <br> *Escherichia coli* (2 isolate)  <br> *Flavobacterium* spp.  <br> *Pseudomonas* spp.  <br> *Streptococcus* spp.  <br> *Aeromonas hydrophila* (ATCC 49140)  <br> *Citrobacter freundii* (ATCC 8090)  <br> *Edwardsiella tarda* (ATCC 15947)  <br> *Pseudomonas aeruginosa* (ATCC 35032), *Streptococcus agalactiae* (ATCC 13813) | ➢ *Cymbopogon nardus* | - | ➢ Overall mean MIC: 0.244 and/or 0.488 µg/mL  <br> ➢ *Edwardsiella* spp. (1 isolate), *E. tarda* (1 isolate), *Aeromonas* spp. (1 isolate) and *Flavobacterium* spp. MIC values: 0.977 µg/mL | Wei and Wee [102] |
Table 3. Cont.

| Bacterial Pathogens | Essential Oil          | Concentrations                        | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen                                                                 |
|---------------------|------------------------|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Lactococcus garvieae | Tanacetum parthenium   | 100 µg/disc and 10 to 1000 µg/mL for MIC | T. parthenium 15 mm/disc and MIC: 824                                                                                     |
|                     | Satureja bachtiarica   |                                       | S. bachtiarica 25 mm/disc and MIC: 126                                                                                   |
|                     |                        |                                       |                                                                                                                          | Fereidouni, et al. [127] |
| Streptococcus iniae | R. officinalis         | 2 mg/disc and 7.8 to 1000 µg/mL MIC and MBC | R. officinalis 45 mm/disc, MIC: 3.9 and MBC: 7.8                                                                          |
|                     | Z. multiflora          |                                       | Z. multiflora 22 mm/disc, MIC: 62.4 and MBC: 250                                                                           |
|                     | graveolens             |                                       | graveolens 32 mm/disc, MIC: 7.8 and MBC: 15.6                                                                             |
|                     | E. globulus            |                                       | E. globulus 18 mm/disc, MIC: 250 and MBC: 250                                                                            |
|                     |                        |                                       |                                                                                                                          | Roomiani, et al. [122] |
| Roomiani, et al.    |                        |                                       |                                                                                                                          |
| Listonella anguillarum | Origanum vulgare subsp. hirtum (7 different collection sample) | 2 µL/disc | O. vulgare subsp. hirtum 9.1 to 14.1 mm                                                                                           |
|                     | O. onites (2 different collection sample) |                                       | O. onites 9.2 and 13.8 mm                                                                                                 |
|                     | O. marjorana           |                                       | O. marjorana 11.5 mm                                                                                                      |
|                     |                        |                                       |                                                                                                                          | Stefanakis, et al. [112] |
| Stefaniak, et al.   |                        |                                       |                                                                                                                          |
| Vibrio splendidus   | O. vulgare subsp. hirtum (7 different collection sample) | 2 µL/disc | O. vulgare subsp. hirtum 7.3 to 14 mm                                                                                           |
|                     | O. onites (2 different collection sample) |                                       | O. onites 12.6 and 14.3 mm                                                                                                 |
|                     | O. marjorana           |                                       | O. marjorana 9.2 mm                                                                                                       |
|                     |                        |                                       |                                                                                                                          | Stefanakis, et al. [112] |
| Stefaniak, et al.   |                        |                                       |                                                                                                                          |
| Vibrio alginolyticus | O. vulgare subsp. hirtum (7 different collection sample) | 2 µL/disc | O. vulgare subsp. hirtum 7.9 to 11.5 mm                                                                                           |
|                     | O. onites (2 different collection sample) |                                       | O. onites 8.6 and 13.6 mm                                                                                                 |
|                     | O. marjorana           |                                       | O. marjorana 7.8 mm                                                                                                       |
|                     |                        |                                       |                                                                                                                          | Stefanakis, et al. [112] |
| Bacterial Pathogens | Essential Oil | Concentrations | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References |
|---------------------|---------------|----------------|-------------------------------------------------------------|------------|
| *Aeromonas salmonicida* (18 isolate) | Origanum onites | 20 µL/disc and 10 to 800 µg/mL for MIC | O. onites 14 to 25 mm/disc and MIC: 800 | Okmen, et al. [97] |
| | Origanum vulgare | | O. vulgare 12 to 26 mm/disc and MIC: 800 | |
| | Thymbra spicata | | T. spicata 10 to 30 mm/disc and MIC: 800 | |
| | Satureja thymbra | | S. thymbra 10 to 30 mm/disc and MIC: 800 | |
| *Flavobacterium psychrophilum* | Rosmarinus officinalis | 0.0, 0.1, 0.3, 0.5, 0.7, 0.9 µL rosemary oil/µL | >-18 mm, 0.1–0.9 µL rosemary oil/disc | Ostrand, et al. [117] |
| *L. garvieae* | Rosmarinus officinalis | 2 mg/disc and 7.8 to 1000 µg/mL MIC and MBC | R. officinalis 24 mm/disc, MIC: 15.6 and MBC: 31.2 | Mahmoodi, et al. [128] |
| | Zataria multiflora Anethum graveolens Eucalyptus globulus | | Z. multiflora 32 mm/disc, MIC: 7.8 and MBC: 15.6 | |
| | | | E. globulus 16 mm/disc, MIC: 250 and MBC: 250 | |
| *Streptococcus iniae* | Thymus daenensis | 100 µg/disc | T. daenensis 19 mm | Pirbalouti, et al. [124] |
| | Myrtus communis | | M. communis 15.67 mm | |
| *L. garvieae* | Zataria multiflora | | Z. multiflora MIC: 4 and MBC: 8 | Goudarzi, et al. [125] |
| | Thymbra spicata | | T. spicata MIC: 8 and MBC: 16 | |
| | Bunium persicum | | B. persicum MIC: 8 and MBC: 16 | |
| | Satureja bachtiarica | | S. bachtiarica MIC: 8 and MBC: 16 | |
| | Thymus daenensis | | T. daenensis MIC: 8 and MBC: 16 | |
| | Myrtus communis | | M. communis MIC and MBC: >1000 | |
| Bacterial Pathogens                          | Essential Oil | Concentrations                                       | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen                                                                 | References                  |
|---------------------------------------------|---------------|------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Lactococcus piscium                        | Thymus vulgaris | 2.5 to 1280 µg/mL for MIC                           | ➢ L. piscium MIC: 320                                                                                                     | Navarrete, et al. [111]     |
| Streptococcus phocae                        |               |                                                     | ➢ S. phocae MIC: 640                                                                                                      |                             |
| Flavobacterium psychrophilum               |               |                                                     | ➢ F. psychrophilum MIC: 320                                                                                               |                             |
| Vibrio ordalii                              |               |                                                     | ➢ V. ordalii MIC: 320                                                                                                     |                             |
| Vibrio anguillarum                          |               |                                                     | ➢ V. anguillarum MIC: 80                                                                                                 |                             |
| Vibrio parahaemolyticus                    |               |                                                     | ➢ V. parahaemolyticus MIC: 320                                                                                             |                             |
| Shewanella baltica                          |               |                                                     | ➢ S. baltica MIC: 640                                                                                                     |                             |
| Pseudomonas sp.                             |               |                                                     | ➢ Pseudomonas sp. MIC: 640                                                                                               |                             |
| Kluyvera intermedia                         |               |                                                     | ➢ K. intermedia MIC: 1280                                                                                               |                             |
| Citrobacter gillenii                        |               |                                                     | ➢ C. gillenii MIC: 1280                                                                                                   |                             |
| Hafnia alvei                                |               |                                                     | ➢ H. alvei MIC: 1280                                                                                                     |                             |
| Psychrobacter sp.                           |               |                                                     | ➢ Psychrobacter sp. MIC: 1280                                                                                             |                             |
| Lactococcus lactis                          |               |                                                     | ➢ L. lactis MIC: 1280                                                                                                     |                             |
| Lactococcus lactis subsp. lactis bv.        |               |                                                     | ➢ L. lactis subsp. lactis bv.                                                                                            |                             |
| diacetylactis                               |               |                                                     | ➢ diacetylactis MIC: 1280                                                                                               |                             |
| Arthrobacter sp.                            |               |                                                     | ➢ Arthrobacter sp. MIC: 1280                                                                                             |                             |
| Lactococcus lactis subsp. diacetylactis     |               |                                                     | ➢ L. lactis subsp. diacetylactis MIC: 1280                                                                                 |                             |
| Arthrobacter sp.                            |               |                                                     | ➢ Arthrobacter sp. MIC: 1280                                                                                             |                             |
| L. lactis subsp. lactis                    |               |                                                     | ➢ L. lactis subsp. lactis MIC: 1280                                                                                       |                             |
| Streptococcus iniae                         | Cinnamomum verum | 10 to 640 µg/mL                                    | ➢ C. verum MIC: 40                                                                                                        | Rattanachaikunsopon and    |
|                                             | Citrus hystrix  |                                                     | ➢ C. hystrix MIC: 160                                                                                                     | Phumkhachorn [123]          |
|                                             | Cymbopogon citratus | 10 to 640 µg/mL                                   | ➢ C. citratus MIC: 320                                                                                                   |                             |
|                                             | Curcuma longa    |                                                     | ➢ C. longa MIC: 160                                                                                                      |                             |
| Flavobacterium columnare (6 isolate)        | Allium tuberosum | 280 µg/mL                                           | ➢ C. tuberosum MIC: 20 to 80                                                                                             | Rattanachaikunsopon and    |
|                                             |               |                                                     |                                                                           | Phumkhachorn [118]          |
Table 3. Cont.

| Bacterial Pathogens                      | Essential Oil          | Concentrations     | Effective Essential Oil/Concentration/Disc/MIC/MBC/Pathogen | References    |
|------------------------------------------|------------------------|--------------------|-------------------------------------------------------------|---------------|
| *Vibrio* spp. (6 isolates) *Edwardsiella* spp. (21 isolates) *Aeromonas* spp. (2 isolates) *Escherichia coli* (2 isolates) *Flavobacterium* spp. *Streptococcus* spp. *Citrobacter freundii* (ATCC 8090), *Pseudomonas* spp. *Citrobacter freundii* (ATCC 8090), *Pseudomonas aeruginosa* (ATCC 35032), *Streptococcus agalactiae* (ATCC13813), *Edwardsiella tarda* (ATCC 15947) | *Syzygium aromaticum* | 0.015 to 0.062 µg/mL | Overall mean MIC: 0.015 to 0.062 | Lee, et al. [103] |
5. Research Gaps and Concluding Remarks

Using of herbal compounds in aquaculture is increasing day by day as a means of aquaculture sustainability. Essential oils (EOs) show beneficial effects on growth, immunity, antibacterial and antiparasitic activities in fish culture and are used as anesthetic compounds during fish handling and transportation. The efficiency of EOs depends on plant variables, chemical compositions of bioactive compounds, environmental characteristics of plant origin, and parts of plants from which EOs is extracted. Sometimes plant originated EOs possess a mixture of different compounds, which may produce undesirable side effects on fish and shellfish. Commercial pharmaceutical companies might play significant roles in refining the desirable and undesirable compounds of EOs to achieve better effects in fish culture.

Importantly, EOs molecular mechanisms for fish immunity increment, bacteria, and parasite destruction are also questionable. Future research through cell culture and in vitro identification and characterization of EOs action pathways may solve these questions. In the upcoming days, EOs optimum doses against infectious bacteria and parasites for worldwide commercial fish species should be extensively studied.

Lastly, the synergistic relationship between/among the bioactive compounds of EOs also opens a new research area. Before applying EOs in aquaculture from any new plants, local and international drug regulating agencies (FDA or EU) permission or guidelines should be needed or followed.

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