antibiotics

Review

Essential Oils as Antimicrobials in Crop Protection

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Abstract: At present, organic crops have reached an important boom in a society increasingly interested in the conservation of the environment and sustainability. It is evident that a part of the population in the Western world focuses their concern on how to obtain our food and on doing it in a way that is as respectful as possible with the environment. In this review, we present a compilation of the work carried out with the use of essential oils as an alternative in the fight against different bacteria and fungi that attack crops and related products. Given the collected works, the efficacy of essential oils for their use as pesticides for agricultural use is evident.

Keywords: essential oil; antibacterial; antifungal; crop protection

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1. Introduction to Essential Oils

Essential oil is a term reserved for those compounds that are defined by the International Organization for Standardization (ISO) [1] in their ISO 9235 [2]. These kinds of compounds are complex mixtures originated from the secondary metabolism [3,4], produced by the glandular trichomes, and in different secretory structures [4,5]. They can be composed by terpenes, associated or not to other components, generally volatile and that provides an odor to the vegetable [6]. These compounds have (with exceptions) a density lower than water density [5,6] and are usually presented in liquid form [5,6]. Besides, essential oils are hydrophobic compounds, soluble in alcohol (among others) and only a little soluble in water [5].

According to the ISO 9235 from the International Organization for Standardization (ISO), the essential oil can be obtained by distillation by any of its variants: hydrodistillation, steam distillation, or dry distillation and by mechanical processes [2]. Some of these distillation methods are widely reported in the literature [7–10], even some variants such as distillation with cohobation [8] have been reported. Because essential oils are responsible for the aroma of plants, they are widely known for their use in cosmetics and perfumery, but they are also an important resource in other industrial fields such as pharmaceutical, food, among others [1,4,5,11]. Indeed, and according to Turek and Stintzing [1], they are a viable environmental-friendly alternative in these fields due to their proved capacity as nematicidal [12,13], antimicrobial [14,15], insecticidal [16], antifungal [15,17] or, even, herbicidal and insect repellent [18]. Besides this, essential oils show antioxidant activity (that can be used in edible products or active packaging) [19], anticancer properties [20], and properties for pain or inflammation treatment [21].

Chemically, essential oils are complex mixtures of more than 100 components [5,11,22], but they are mainly made up of terpenic compounds [23]. Terpenoids, sometimes called isoprenoids, are a broad family of natural compounds derived from isoprene [24]. About 60% of known natural products are terpenoids [25]. This class of secondary compounds (essential oils) contains different terpenoids such as monoterpenes (C_{10}) [18,26] contain two isoprene units (linear or cyclic [26]) like myrcene, menthol, limonene, or linalool (see

Figure 1). Other important components of essential oils are the sesquiterpenes which consist of three isoprene units (C_{15}) [18,26]. Figure 1 shows some different sesquiterpenes such as patchoulol or nootkatone (see Figure 1). According to the information reported by Martinez (2003) [11], monoterpenoids are common in the Primulales, Ranunculales, and Violales orders (being scarcer in other different orders such as Asterales, Cornales, Lamiales, and Rutales) and sesquiterpenoids are mainly abundant in other orders such as Asterales, Cornales, Magnoliales, and Rutales [11]. Essential oils can also contain diterpenes (as by-product) [26] which are composed of four isoprene units -as retinal or phytol-. Finally, essential oils contain other compounds such as aromatic phenols, ethers, esters, alcohols, among others, which will confer the aroma and odor of the plant [18].

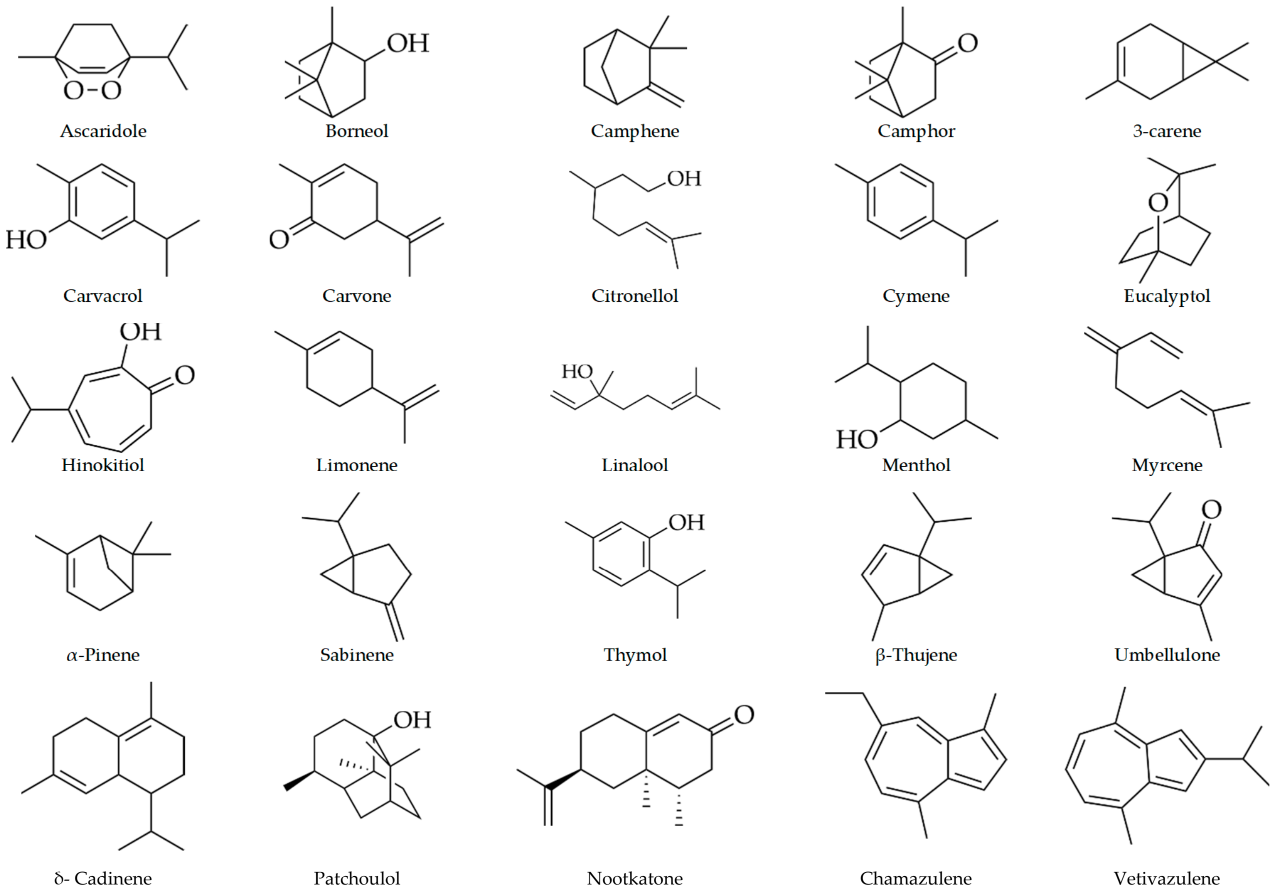

Figure 1. Some monoterpenoids and sesquiterpenoids presented in essential oils.

Essential oil components can convert without difficulty into each other by a different process (cyclization, isomerization, oxidation, among other ways) due to their structural relation inside the same chemical group [1].

The chemical composition of essential oils depends on different factors such as plant's physiology, climate characteristics or, even, soil conditions where the plant grows [3]. According to this, within the same plant species, or even in their different organs, the chemical composition may vary [3]. The chemical composition can also be influenced by plant health or harvest time [1].

According to Montoya Cadavid [27], around 60 and 80 families produce essential oils, the largest number grows in tropical climates, although they are also found in other climates, with the spermatophytes as the main plants that produce essential oils. Essential oils are found in the different organs of the plant [11,27]: roots (e.g., turmeric, saffron, ginger, and sandalwood), flowers (e.g., thyme, lavender, arnica, and chamomile), fruits (e.g., laurel, coriander, parsley, or pepper), and in other parts such as seeds or leaves, among others.

2. Essential Oils as Antibacterial and Antifungal Compounds

Many secondary metabolites produced by plants can present an important role in their protection against microbes potentially pathogenic [4]. These compounds are a very attractive alternative to many antibiotics due to the bacterial resistance generated to traditional products [4]. An example of this is the use of genus Origanum or Thymus due to their antimicrobial activity. However, many times these studies are only focused on the antibacterial activities and do not enter to assess the action mechanism [4].

The following sections present plants whose essential oils have toxic action against a certain organism. The classification contains bacteria and fungi that can affect crop production and other plants and products of interest.

2.1. Antibacterial Activity

Many pathogenic bacteria in crops can cause serious problems and symptoms in the different parts of the plants such as spots, cankers, rots, wilting, among others [28–32]. Different studies have shown that essential oils present antibacterial properties against pathogens which can cause post-harvest diseases in vegetables and fruits [32]. In fact, the use of plants, herbs, or spices (for medical, preservatives, and/or pest control) has been reported since ancient civilizations of Egypt, Greece, Rome, among others [33–35] and their properties have been systematically analyzed in laboratories since the beginning of the last century [36,37], and even before. Besides, they have demonstrated their efficacy against multidrug-resistant/antibiotic-resistant bacteria [38,39].

Essential oils present different components and it is possible that their action implicates different targets in the bacteria cell [40]. Their cytotoxic properties are due to the disruption of membranes structure that results in bacterial cell permeabilization so different cellular functions (membrane potential, among others) are altered [4]. It can be said that their antimicrobial activity is due to the solubility of essential oils in the bilayer [41].

The use of essential oils (or their respective plants of origin) to combat this type of organism is not a minor issue, due to bacteria leading different diseases on plants which can have a notable economic impact [42]. Due to this, in recent years, numerous studies have been carried out on the antibacterial properties of essential oils against different pathogens that can attack plants, and even food [42].

Table 1 shows a compilation of research articles [43–57] in which different plants/essential oils were analyzed by their possible antibacterial activity that can affect both crops and stored products, among others. This table contains part of the experimental work developed by the researchers (for a better understanding, consult the original sources). All these studies can be the initial step for the development of new products to combat these types of pathogens.

Table 1. Plants that present essential oils that could be used for their antibacterial properties.

Plant			
Common Name	**Scientific Name**	**Organism to Fight against**	**Ref.**
Sandalwood	*Amyris balsamifera*	*Xylella fastidiosa*	[43]
Dill	*Anethum graveolens*	*Streptomycetes scabies*	[44]
Caraway	*Carum carvi* L.	*Agrobacterium tumefaciens*	[45]
		Bacillus megaterium	
		Clavibacter michiganensis subsp. *michiganensis*	
		Clavibacter michiganensis subsp. *sepedonicus*	
		Curtobacterium flaccumfaciens pv. *betae*	
		Curtobacterium flaccumfaciens pv. *flaccumfaciens*	
		Erwinia carotovora subsp. *atroseptica*	

Table 1. *Cont.*

Plant			
Common Name	**Scientific Name**	**Organism to Fight against**	**Ref.**
Caraway	*Carum carvi* L.	*Ralstonia solanacearum*	[45]
		Xanthomonas campestris pv. *campestris*	
		Xanthomonas campestris pv. *phaseoli*	
		Xanthomonas campestris pv. *phaseoli var. fuscans*	
		Xanthomonas campestris pv. *vesicatoria*	
Cinnamon	*Cinnamomum verum*	*Acidovorax citrulli*	[46]
		Ralstonia solanacearum	[47]
Cumin	*Cuminum cyminum* L.	*Agrobacterium tumefaciens*	[45]
		Clavibacter michiganensis subsp. michiganensis	
		Clavibacter michiganensis subsp. *sepedonicus*	
		Curtobacterium flaccumfaciens pv. *betae*	
		Curtobacterium flaccumfaciens pv. *flaccumfaciens*	
		Erwinia carotovora subsp. *atroseptica*	
		Ralstonia solanacearum	
		Rhodococcus fascians	
		Xanthomonas campestris pv. *phaseoli*	
		Xanthomonas campestris pv. *phaseoli* var. *fuscans*	
		Xanthomonas campestris pv. *vesicatoria*	
Palmarosa	*Cymbopogon martini*	*Ralstonia solanacearum* Race 4	[48]
Lemongrass	*Cymbopongo citratus*		
Common juniper	*Juniperus communis*	*Enterococcus faecalis*	[49]
		Listeria monocytogenes	
		Staphylococcus aureus	
Cade juniper	*Juniperus oxycedrus*	*Enterococcus faecalis*	
		Listeria monocytogenes	
		Staphylococcus aureus	
Common lantana	*Lantana camara*	*Ralstonia solanacearum* phylotype II	[50]
Lemon blam	*Melissa officinalis*	*Pantoea agglomerans*	[51]
		Pseudomonas fluorescens	
		Pseudomonas syringae pv. *syringae*	
Corn mint	*Mentha arvensis*	*Erwinia amylovora*	
		Pantoea agglomerans	
		Pseudomonas syringae pv. *syringae*	
Peppermint	*Mentha piperita*	*Acidovorax citrulli*	[46]
Mint	*Mentha spicata*	*Bacillus subtilis*	[52]
		Erwinia carotovora	
		Escherichia coli	
		Klebsiella pneumoniae	
		Staphylococcus aureus	
		Xanthomonas campestris	

Table 1. *Cont.*

Plant			
Common Name	**Scientific Name**	**Organism to Fight against**	**Ref.**
Catnip	*Nepeta cataria*	*Erwinia amylovora*	[51]
		Pantoea agglomerans	
Sweet basil	*Ocimum basilicum*	*Acidovorax citrulli*	[46]
	Origanum compactum	*Erwinia amylovora*	[51]
		Pantoea agglomerans	
		Pantoea dispersa	
		Pseudomonas fluorescens	
		Pseudomonas syringae pv. *syringae*	
Dictamnus	*Origanum dictamnus*	*Clavibacter michiganensis* subsp. *michiganensis*	[53]
Marjoram	*Origanum majorana*	*Clavibacter michiganensis* subsp. *michiganensis*	
Origanum	*Origanum majorana* L.	*Acidovorax avenae* subsp. *citrulli*	[54]
Oregano	*Origanum onites*	*Streptomycetes scabies*	[44]
Oregano	*Origanum vulgare*	*Clavibacter michiganensis* subsp. *michiganensis*	[53]
		Erwinia amylovora	[51]
		Pantoea agglomerans	
		Pantoea dispersa	
		Pseudomonas fluorescens	
		Pseudomonas syringae pv. *syringae*	
Patchouli	*Pogostemon patchouli*	*Xylella fastidiosa*	[43]
	Satureja adamovicii Šilić	*Erwinia amylovora*	[55]
	Satureja fukarekii Šilić		
Summer savory	*Satureja hortensis*		[56]
	Satureja kitaibelii Wierzb. ex Heuff.		[55]
	Satureja montana ssp. *montana* L.		
Clove bud	*Syzygium aromaticum*	*Acidovorax citrulli*	[46]
Thyme	*Thymbra spicata* L. subsp. *spicata*	*Acidovorax avenae* subsp. *citrulli*	[54]
Thyme	*Thymus capitatus*	*Clavibacter michiganensis* subsp. *michiganensis*	[53]
Thyme	*Thymus serpyllum* L.	*Acidovorax avenae* subsp. *citrulli*	[54]
Thyme	*Thymus vulgaris*	*Erwinia amylovora*	[51]
			[56]
		Pantoea agglomerans	[51]
		Pantoea dispersa	
		Pseudomonas fluorescens	
		Pseudomonas syringae pv. *syringae*	
Ajowan	*Trachyspermum ammi*	*Erwinia carotovora*	[57]

2.2. Antifungal Activity

Essential oils have also been presented in antifungal properties. The fungal diseases can have different consequences on plants such as alterations in their physiology, disturb their usual functioning, reduce their performance and, even, sometimes the loss of the plant [58]. Different essential oils from plants (and their dominant constituents) have proved antifungal activity against different plant pathogenic fungi [59]. According to Isman and Machial [59], their action mechanisms is unknown but can be linked to their capacity to dissolve/disrupt the integrity of the fungi's membranes and cell walls. According to Arraiza et al. [58], in different studies, the antifungal properties are based on the inhibition of fungal mycelial growth in vitro. However, it is necessary to be careful with the use of essential oils because many of these oils (and their pure compounds) can present high phytotoxicity for plants (even in concentrations slightly higher than those necessary for the control of fungi), possibly due to plant cells being affected by the same mechanism [59].

Table 2 shows a compilation of research articles [53,60–72] in which different plants/essential oils were analyzed by their possible antifungal activity. As previously said, this table contains only a part of the experimental work (for a better understanding, consult the original sources).

Table 2. Plants and essential oils that could be used for their antifungal properties.

Plant			
Common Name	**Scientific Name**	**Organism to Fight against**	**Ref.**
	Cinnamomum camphora var. *Linaloolifera*	*Alternaria solani*	[60]
Cinnamon bark oil	*Cinnamomum cassia*	*Villosiclava virens*	[61]
Cinnamon oil			
Gingergrass	*Cymbopogon martinii*	*Fusarium graminearum*	[62]
	Cymbopogon martinii (chitosan nanoparticles)		
Lemongrass	*Cympopogon citratus* L.	*Botrytis cinerea*	[63]
		Cladosporium herbarum	
		Colletotrichum coccodes	
		Rhizopus stolonifer	
River red gum	*Eucalyptus camaldulensis* Dehnh.	*Fusarium oxysporum*	[64]
		Fusarium proliferatum	
		Fusarium solani	
		Fusarium subglutinans	
		Fusarium verticillioides	
Eucalyptus	*Eucalyptus citriodora*	*Venturia inaequalis*	[65]
Southern blue gum	*Eucalyptus globulus*	*Alternaria solani*	[60]
Lemon-scented ironbark	*Eucalyptus staigeriana*		
Espliego	*Lavandula latifolia* Medik.	*Fusarium moniliforme*	[66]
		Fusarium oxysporum	
		Fusarium solani	
Lavandín	*Lavandula* x intermedia Emeric ex Loisel.	*Fusarium moniliforme*	
		Fusarium oxysporum	
		Fusarium solani	
Prontoalivio	*Lippia alba* (Mill.) N.E. Brown (Chemotype Caxias do Sul)	*Alternaria solani* (Pleosporeaceae)	[67]
	Lippia alba (Mill.) N.E. Brown (Chemotype Pelotas)		
	Lippia alba (Mill.) N.E. Brown (Chemotype Santa Vitória do Palmar)		
	Lippia alba (Mill.) N.E. Brown (Chemotype Teutônia)		

Table 2. *Cont.*

Plant			
Common Name	**Scientific Name**	**Organism to Fight against**	**Ref.**
Tea tree	*Melaleuca alternifolia*	*Blumeria graminis*	[68]
		Fusarium culmorum	
		Fusarium graminearum	
		Pyrenophora graminea	
White basil	*Ocimum basilicum L.*	*Alternaria solani Sorauer*	[69]
Genovese basil	*Ocimum basilicum L.* var. *Genovese*		
	Ocotea quixos (Lam.) Kosterm	*Aspergillus oryzae*	[70]
		Cladosporium cladosporioides	
		Fusarium solani	
		Moniliophthora roreri	
		Phytophthora sp.	
		Rhizopus stolonifer	
Dictamnus	*Origanum dictamnus*	*Botrytis cinerea*	[53]
		Fusarium solani var. coeruleum	
Marjoram	*Origanum majorana*	*Botrytis cinerea*	
		Fusarium solani var. coeruleum	
Oregano	*Origanum vulgare*	*Botrytis cinerea*	
		Fusarium solani var. coeruleum	
Jamaica pepper	*Pimenta dioica* (L.) Merr.	*Aspergillus flavus*	[71]
		Aspergillus fumigatus	
		Fusarium oxysporum	
		Fusarium verticillioides	
		Penicillium brevicompactum	
		Penicillium expansum	
Anise	*Pimpinella anisum* L.	*Alternaria solani Sorauer*	[69]
Spiked pepper	*Piper aduncum* L.	*Fusarium solani*	[70]
		Phytophthora sp.	
Caisimón de anís	*Piper auritum* Kunth	*Alternaria solani Sorauer*	[69]
Clove	*Syzygium aromaticum*	*Penicillium digitatum Sacc.*	[72]
		Venturia inaequalis	[65]
Thyme	*Thymus capitatus*	*Botrytis cinerea*	[53]
		Fusarium solani var. coeruleum	
	Thymus vulgaris L.	*Fusarium moniliforme*	[66]
		Fusarium oxysporum	
		Fusarium solani	

3. Advantages and Drawbacks of Essential Oils Based Biopesticide for Crop Protection Control

Many studies have shown that different constituents of essential oils can present antibacterial and antifungal properties so that there are real possibilities to used essential oils for plants and crop protection. These kinds of products, made based on essential oils, could be considered as biopesticides. However, different authors suggest that the term "biopesticide" should be reserved only for living organisms (biological agents) [73,74]. This definition is too restrictive and would not include different products derived from the metabolism of the biological organisms [73,74] (plants in our case). Thus, in the current crop protection situation, a wide definition of biopesticides could encompass all compounds of biological origin and seem more suitable [73].

Essential oils-based biopesticides present some advantages for crop protection. Numerous essential oils, that have a large number of plants, cover a wide spectrum of activities against pest insects and pathogenic fungi [75]. These compounds show highly useful against a broad range of agricultural pests and diseases [76]. They present a low persistence in the medium due to its high volatility [75] so that they produce little or no toxic residue and as a result, they do not pollute the soil or groundwater. Besides this, the most essential oils are reasonably nontoxic to mammals and aquatic life and they can be classified as low-risk pesticides [75], in other words, essential oils could present low toxicity against non-target organisms [76]. Another advantage of this group of compounds is that some essentials oils are available in large measure, due to this, the commercialization of pesticides based on essential oils is possible [75], besides, for its application, the same spray equipment can be often used [77] which means that the end-user should not acquire any new equipment for the use of these biopesticides.

On the other hand, and due to that essential oils are a complex mixture of compounds, the possible development of resistance by the pest is slow [75] or less probable [76]. Finally, the use of biopesticides frequently presents good compatibility with conventional chemical pesticides and with biological pest control agents [77].

Although essential oils (and biopesticides in general) have shown many advantages over the use of traditional/conventional pesticides, they present several disadvantages. At the commercial level, not many kinds of this product have arisen in the market, probably due to the high cost of necessary evaluations (toxicology and environmental) [75] because the authorization processes of these biopesticides (botanical pesticides) are complex [76]. Furthermore, according to Isman [78], it would be necessary to have sufficient availability, uniformity, and purification technology protection and a homologation following a regulatory framework. Besides, essential oils are a complex mixture of compounds (beneficial effect to slow down resistance [75,76]), nevertheless, the characterization and specificity detection of each compound that constitutes the essential oil is inaccessible for their use in agricultural farms [75].

On the other hand, some biopesticides can show low persistence (something positive) but they can also be considered as a drawback after application [79] because essential oils can suffer gradual biodegradation of their active substances after application [76]. Related to this, essential oil-based pesticides present less effective when they are compared with other synthetic/conventional chemical pesticides [75,77]. Finally, these kinds of pesticides generally require higher application rates, which together with the need to apply the product frequently, makes their use expensive and time-consuming [75].

To finish, Pavela and Benelli [76] reported that there are numerous studies centered on the biological activity of essential oils on target organisms, nevertheless, it would be necessary to further research toxicological studies and the possible effects of their use on non-target ones. Furthermore, according to the same authors [76], the mechanisms of action and other properties of interest have not yet been clarified. Despite this, the authors report that based on the existing toxicological studies, it can be concluded that the most essential oils can be considered safe (for human and the environment) in the concentrations or doses commonly used, and based on this, the legislation could be simplified and establish a greater partnership between research and the manufacturers of botanical pesticides [76].

4. Conclusions

It seems clear that there are many and different characteristics that can be attributed to essential oils. All of these comes from studies developed in recent decades that have been carried out based on their biological activity and their use in different fields such as agronomy and food production. These studies have shown the relative efficacy of the use of the essential oils against different types of organisms, their action mechanisms, and their low toxicity in mammals and humans.

Their possible use presents, as expected, advantages for the environment such as their volatility (less persistent than other synthetic chemicals) or that they are a new alternative to the resistance to synthetic chemicals by organisms. As main drawbacks, those related to their availability, the high cost of the authorization processes, their low persistence, and less effective action. On the other hand, it is necessary to determine their optimal ratio and dosages to improve their efficacy and decrease their toxicity, all these aimed to have sufficient scientific information to be able to be safely marketed.

Essential oils could mean the appearance of a new era of plant protection products to control the microbial pathogens and prevent their propagation and resistance.

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