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Essential Oils for Pest Control
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Orange Oil

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15.1 Introduction

Orange oil is an essential oil (EO) produced by cells within the rind of the orange fruit, which is extracted as a by-product of orange juice production by centrifugation due to numerous domestic, industrial, and medicinal uses [1]. Being nontoxic, nonirritating, and nonsensitizing, orange oil is granted the generally recognized as safe (GRAS) status in the United States by the Food and Drug Administration (GRAS 182.20). EO is mostly composed of (greater than 90%) d-limonene, a highly valued terpene [2]. Although present in minor amounts, other components are important to enhance, for example, the plant antifungal and antibacterial properties with respect to pure d-limonene, as first reported in 1993 by Singh and colleagues [3].

First registered as an insecticide in the United States in 1958 (and later as an antibacterial in 1971), d-limonene extracted from orange oil by distillation has been among the first natural pesticide ingredients used in environmentally friendly pest control. We note here that *plant pest* means any organism causing a detrimental effect on the plant's health and vigor, including fungi, bacteria, viruses, molds, insects, mites, and nematodes, but excluding mammals, fish, and birds.

Today, the great potential of *Citrus sinensis* essential oil in crop protection against insect pests is well established, although perhaps little known among farmers (the pesticide users) and even chemical research practitioners (the pesticide developers) [4].

Orange essential oil is furthermore highly effective as a contact insecticide against ants, roaches, palmetto bugs, fleas, silverfish, and many home and garden insects, including houseflies and their larvae and pupae [5]. Several insecticide products are available in the marketplace, along with the first crop biopesticides.

Owing to their low toxicity, nonpersistence in the environment, and good repellent, insecticidal, and growth-reducing activities on a variety of insects [6], in a trajectory common to several other functional products, driven by health and environmentally conscious users and consumers, pest and insect repellents, originally developed via synthetic organic chemistry in the early 1920s, have evolved to rediscover low-risk essential oils [7].

Several thorough studies on botanical pesticides have been published [8], including recent accounts that assess the current and future situation of biopesticides, especially focusing on their potential within the European pesticide legislative framework [9]. In 2008, Isman, whose research group in Canada has pioneered the field, argued that the greatest benefits from botanicals might be achieved in developing countries where human pesticide poisonings are prevalent [10], whereas their use in industrialized countries would be more restricted to pest control in and around homes and gardens, in food storage facilities, and on companion animals.

Reviewing recent research and industrial achievements, in this chapter we summarize the main features of orange oil as a biopesticide. We conclude by suggesting arguments for which the employment of this valued natural product as an environmentally friendly biopesticide will be a central tenet of the emerging bioeconomy not only in organic food production, but also in conventional agriculture, where it will replace a number of synthetic pesticides.

15.2 Composition, Toxicity, and Biological Activity

In general, the composition varies with the cultivated species of the *Citrus* genus, geographical origin, harvesting (and thus weather) conditions, and extraction method. For example, the limonene content in the same Valencia orange crop may range from 91.4% in vacuum-distilled concentrates [11] to 97.0% in cold-pressed concentrates [12]. From now on, we will refer to sweet orange oil, namely, the oil obtained from *C. sinensis* (sweet orange). Note that *Citrus* is a large genus beyond *C. sinensis* that originated from a backcross hybrid between pummelo and mandarin [13]; it includes several major cultivated species, such as *Citrus reticulata* (tangerine and mandarin), *Citrus limon* (lemon), *Citrus grandis* (pummelo), and *Citrus paradisi* (grapefruit).

Figure 15.1 displays the chemical structures of selected components of orange essential oil. Along with dominant d-limonene (>90%), the principal components of orange oil are monoterpenes (α-pinene, sabinene, and β-myrcene), followed by oxygenated compounds such as alcohols (linalool and α-terpineol) and aldehydes (geranial, neral, and citronellal), including long-chain aliphatic aldehydes like decanal and octanal [14].

The orange color is due to the presence of polymethoxyflavones, such as sinestetin, tangeretin, quercetogetin, nobiletin, and heptamethoxyflavone (Table 15.1), which, like other flavonoids, show strong antifungal activity [15], besides playing an important role as antioxidants and enzyme inhibitors.

Remarkably, from the applicative viewpoint, significant differences exist in the oil composition between orange oils obtained using biological cultivation and those obtained through traditional cultivation using organophosphorus and organochlorine pesticides [14]. In particular, the content of aliphatic aldehydes is much lower (0.22%) in orange oil obtained from traditionally grown fruits than that (0.79%) found in oil extracted from organically grown fruits. These aldehydes, especially decanal and octanal, characterize the olfactory notes of sweet orange oils. Furthermore, the amount of terpene aldehydes neral and geranial, the so-called “citral” substances that determine lemon oil olfactory peculiarity and the economic value of the oil in the perfume market, was considerably higher in oil from organically grown crops (2.90%) than in oil from conventionally grown fruits (2.41%).

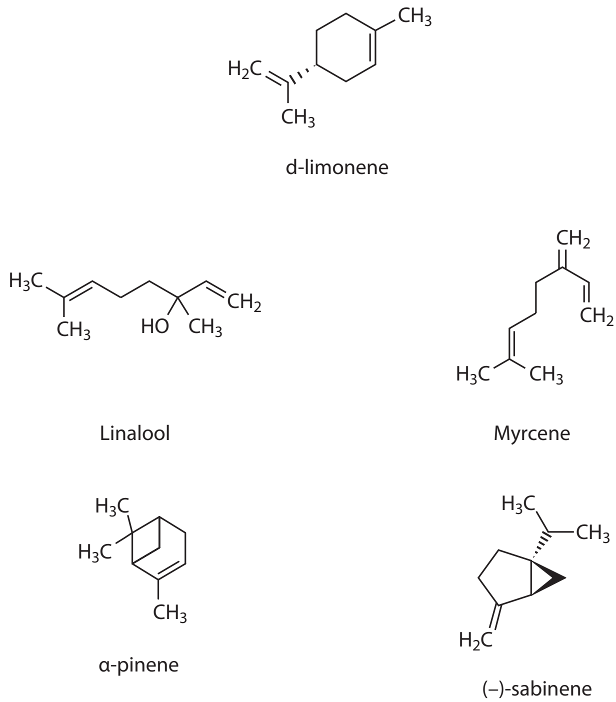

FIGURE 15.1
Chemical structures of the main components of orange oil.

TABLE 15.1
Polymethoxyflavone Content in Sweet Orange Oil Isolated in Spain

Flavonoid	Concentration (g/L)
Sinensetin	0.1
Quercetogetin	0.1
Nobiletin	1.0
Tangeretin	0.5
Heptamethoxyflavone	2.5

Source: Reproduced from Del Río, J. A. et al., *J. Agric. Food Chem.*, 46, 4423–4428, 1998. With permission.

Renewable d-limonene extracted from orange oil occurs naturally in food and is therefore classified by the U.S. Food and Drug Administration as a GRAS food additive to baked goods, ice cream products, gelatins, puddings, and chewing gum. With a few exceptions, its mammalian toxicity is low and its environmental persistence is very short. It is practically nontoxic to mammals [16] and birds, and slightly toxic to freshwater species, both fish and invertebrates.

The constituents of orange oil are quickly degraded in the open environment, thanks to rapid oxidation. In general, d-limonene has poor solubility in water (13.8 mg/L), and it is highly resistant to microbial biodegradation in water and soil due to its well-known antimicrobial activity. It rapidly volatilizes from both dry and moist soil to the atmosphere, where it rapidly undergoes gas phase oxidation reactions with photochemically produced hydroxyl radicals, ozone, and at night, nitrate radicals, with calculated half-lives for these processes on the order of <2 h. A similar fate is expected for the other components, indicating little or no persistence in the environment, and thus no bioaccumulation or biomagnification.

The aerial oxidative degradation compounds of d-limonene, and limonene 1,2-oxide in particular, are respiratory irritants [17], although having short lives, and may cause adverse skin reactions. Hence, during plant protection with orange oil, applicators will use proper equipment observing the labeling recommendations aimed at minimizing exposure from dermal contact or inhalation during delivery by spraying or fogging. For example, public authorities in Canada require that when applying a new orange oil–based insecticide formulation for commercial environments, applicators "wear long pants, a long-sleeved shirt, shoes plus socks, goggles or face shield, and chemical-resistant gloves [18]."

As mentioned above, the plant protection properties of EOs, and orange essential oil in particular, have long been known. It is perhaps not surprising that in 2009 researchers in Greece reported that orange oil is an excellent pesticide against neonates of the Mediterranean fruit fly, namely, the *Ceratitis capitata*, causing frequent infestation of citrus fruits plantations [19]. Administering larvae with diets containing orange oil caused rapid mortality, with LC_{50} values ranging from 7 to 11 ml/g.

In 1991, Coats and colleagues were the first to ascribe to neurotoxicity the significant biological effects and symptoms observed—hyperactivity, loss of coordination, tremors, trembling, and paralysis of legs, followed by convulsions and death—when insects came into contact with monoterpenoids. "Symptoms of acute poisoning of insects by orange oil monoterpenoids are similar to those effected by some neurotoxic compounds [20]." The same team in 1988 had reported that d-limonene found in the essential oil of various citrus leaves and fruit peels exhibits significant insect control properties [21]. Today, we know that monoterpenoid compounds exert their activities through neurotoxic effects involving several mechanisms that affect multiple targets, thereby more effectively disrupting cellular activity and biological processes of insects [6].

In 2015, Kourimska and colleagues in Czechia completed a landmark study for future applications of orange oil to crop protection. The research team tested *C. sinensis* essential oil in wheat protection against *Oulema melanopus L.* (*Coleoptera: Chrysomelidae*) [4], a small cereal leaf beetle feeding on various grasses that can cause economically important damage, especially on wheat and barley.

Tested against *O. melanopus* larvae and adults under laboratory conditions, the oil showed remarkably high direct contact toxicity against the larvae, causing mortality of 85% during 48 h (Table 15.2). The larvae cause damage to the growing plant during the last stage of development. A high dissipation rate of the oil from treated plants (concentration lower than 0.01 g/kg 5 min after application of the oil) clearly points to its low persistency (Figure 15.2), and thus to its environmental and food safety.

Adding relevance to the use of orange oil as a biopesticide that goes well beyond use in homes and gardens, in 2013 researchers in Greece discovered that the oil is an excellent pesticide against the vine mealybug, a grape vine pest that is affecting an increasing number of grape vine–growing areas worldwide [22].

In detail, bioassays were conducted in the laboratory by spraying an aqueous solution of the EO obtained via hydrodistillation of orange or lemon peels (using 1% Tergitol as an emulsifier) directly on grape leaves bearing field representative clusters of *Planococcus ficus*.

The results clearly show the high insecticidal activity and the lack of any phytotoxic effect on grape vine by citrus orange and lemon oils. The LC_{50} and LC_{90} mortality data

TABLE 15.2

Mortality of *Oulema melanopus* Larvae and Adults after Apical Application of *Citrus sinensis* Essential Oil

Exposition Time (h)	Larvae (%)	Adults (%)
1	12.5	0
24	42.5	0
48	85.0	0

Source: Reproduced from Zarubova, L. et al., *Acta Agric. Scand. Sect. B*, 65, 89–93, 2015. With permission.

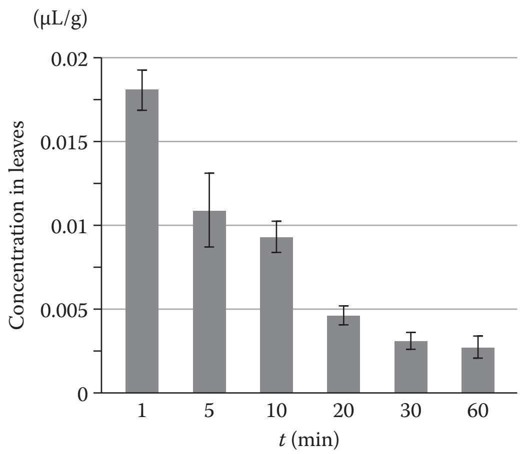

FIGURE 15.2
Concentration of *C. sinensis* essential oil after application on wheat leaves. Bars indicate standard error. (Image courtesy of the Florida Chemical Company; Lenka Zarubova et al. *Acta Agric Scand B Plant Soil Sci*, 2015.)

values (lethal concentration where 50% and 90% of the population is destroyed, respectively) in the two pest life stages studied were significantly lower than the corresponding values of the reference paraffin oil, pointing to a higher toxic effect of the orange oil than that of the reference product.

Referring to the previous work of Hollingsworth, dating back to 2005 [23], the team emphasized the importance of a good emulsion when mixing the oil with water in the presence of the required surfactant in order to prevent the two stages of phase separation of the formulation, and thus variability of the EO insecticidal effect on the target pest and cause of phytotoxicity to the plant. In detail, Hollingsworth identified a 1% limonene, 0.75% APSA-80 (a nonionic surfactant functioning as a spray adjuvant), and 0.1% Silwet L-77 (a superspreading surfactant based on a trisiloxane ethoxylate surfactant) microemulsion as a suitable spray biopesticide providing superior control of mealybugs when sprayed on green scales on potted gardenia plants, averaging 95% mortality, in comparison with 89% and 88% mortality on plants sprayed with insecticidal soap or horticultural oil, respectively.

The relevance of the right choice of the surfactants in formulating orange oil as a biopesticide is demonstrated by the successful introduction of PREV-AM, the first orange oil–based biopesticide commercialized on a global scale.

In detail, PREV-AM is the trade name of the orange oil formulation in water with borax (sodium borate) and biodegradable surfactants, such as, originally, ethoxylated alcohols and alcohol ethoxy sulfate [24]. It is owned by Oro Agri, a South African company with production sites in Africa, Europe, and the United States. Manufactured in Spain and California in large and increasing amounts, PREV-AM Plus is a biopesticide containing 60 g/L orange oil, along with borax and a blend of surfactants, such as ethoxylated alcohols, alkyl glucoside polysaccharides, urea, and parabens, as preservatives [25]. Lately, it has been used as a multipurpose contact insecticide, fungicide, and acaricide in many of the world's countries for the eco-friendly treatment of several pest-mediated diseases, such as powdery mildew fungus (*oidium tuckery*) affecting grape crops [26]. The formulation provides highly effective contact activity against various insects, fungi, and mites, acting as an alternative to conventional pesticides.

In 2015, the product gained approval by Italy's Health Ministry for the treatment of a number of plant pest-induced diseases [27]. For example, it fights against the vector of the *Xylella fastidiosa* bacterium that is severely hitting olive orchards in Italy's Puglia. Formulated in the PREV-AM composition, orange oil has shown particularly good efficacy in killing the *Philaneus spurmarius* insect that acts as a vector of the plant pathogenic bacterium that lives inside the xylem vessels of the host plant, where it forms a biofilm that disrupts the passage of water and nutrients within the plant. Applied at an optimal rate of 8 L/ha, the biopesticide desiccates the cuticles of the insects that are carriers of *Xylella bacteria*, leading to suffocation and death.

Assessed by acute toxicity tests carried out in the open field, the toxicity of PREV-AM to predatory mites on strawberry (tested in 2013 in California) and on grape (tested in 2009 in Czechia) and to honeybees (tested in 2013 in Germany) is low [28]. Indeed, the formulation is approved for organic farming, even though acute toxicity assessment alone cannot fully predict the actual impact of biopesticides on nontarget parasitoids, requiring full consideration of sublethal effects and longer-term population dynamics in order to assess pesticide risks [29].

Pointing to the usefulness of orange oil as a postharvest freshness-saving agent, researchers in Korea recently showed that orange oil is also suitable as a new fumigant for the control of two grain storage insects, adults of the maize weevil (*Sitophilus zeamais*) and the red flour beetle (*Tribolium castaneum*), against which it shows strong fumigant and contact activity [30]. Except for linalool, which shows exceptionally high toxicity, the toxicity of the oil in contact and fumigant toxicity tests (Table 15.3) was higher than that of its

TABLE 15.3

Fumigant Toxicity of Basil Oil, Orange Oil, and Their Components against *Sitophilus zeamais* and *Tribolium castaneum* Adults, 24 h

EO/Terpene	*S. zeamais* LC_{50} (mg/ml)	*T. castaneum* LC_{50} (mg/ml)
Orange oil	0.106	0.130
Limonene	0.122	0.171
Linalool	0.016	0.023
β-Myrcene	0.274	0.275
α-Pinene	0.264	0.273

Source: Reproduced from Ministero della Salute, Decreto Autorizzazione in deroga per situazioni di emergenza fitosanitaria, ai sensi dell'art, 53, paragrafo 1, del regolamento (CE) n. 1107/2009, del prodotto fitosanitario denominato PREV-AM PLUS reg. n. 16379, contenente la sostanza attiva olio essenziale di arancio dolce, May 13, 2015. See http://www.salute.gov.it/imgs/C_17_pagineAree_1110_listaFile_itemName_35_file.pdf.

constituents (α-pinene, 0.54%; sabinene, 0.38%; β-myrcene, 1.98%; d-limonene, 96.5%; and linalool, 0.6%). Suggesting a respiratory mode of action, the toxicity was mainly exerted by fumigant action via the vapor phase.

Orange oil is highly effective in killing and repelling entire ant and termite colonies, preventing reinfestation. Indeed, orange oil showed both contact and fumigant toxicity, dissolving and dispersing the pheromone trail left behind by ants so that new ants cannot follow it back to the original nesting spot. For example, dispersing orange oil (~92% d-limonene) at concentrations as low as 5 ppm (v/v) in the vapor phase causes practically complete (96%) mortality to the Formosan subterranean termite (*Isoptera: Rhinotermitidae*) within 5 days [31]. Furthermore, termites did not tunnel any longer through glass tubes fitted with sand treated with 0.2%–0.4% orange oil.

15.3 Open Challenges

Several home insecticides based on water-based formulated orange oil are available in the marketplace, especially in North America, for instance, *Orange Guard*, *Ortho Home Defense Indoor Insect Killer*, *Concern Citrus Home Pest Control*, *Safer Fire Ant Killer*, and *Citrex Fire Ant Killer*. Yet, to the best of our knowledge, only one pesticide to protect plants against weeds, pests, and diseases has been commercialized.

Hence, it is natural to ask, why are there so few products commercially available in 2017, when the sustainability issue has emerged as a central global problem?

One might think that the procedure for regulatory approval of plant protection products is too expensive. Yet, the United States reduced and released the regulation process for GRAS biopesticides, establishing a simplified procedure, as early as 1996. In only 5 years, this single policy act led to a large diversity of EO-based insecticide products available to users in the U.S. marketplace [6].

In Europe, in 2009 the European Food Safety Authority published its review of orange oil risk assessment [17], which was used in 2013 by the European Commission to approve the PREV-AM biopesticide containing orange oil for control of sweet potato whitefly, *Bemisia tabaci*, on field pumpkin (*Cucurbita pepo*) and for control of greenhouse whitefly on tomato. The same PREV-AM nonpersistent formulation provides insecticide, fungicide, and acaricide activity on a wide range of crops, and thanks to this company, orange oil is now present in the European approved pesticide substance list. Reduced and flexible regulation for essential oil products that not only do not have a history of adverse effects, but also show significant health beneficial effects, is thus in place.

In our viewpoint, there are three reasons for which orange oil pesticides are not yet massively marketed. First, strong competition exists from readily available synthetic pesticides in a global market historically controlled by large chemical companies [32]. It is revealing, in this respect, to learn that recently the world's largest chemical company applied and got registration in Canada for its orange oil–based insecticides, *MotherEarth Botanical Crawling Insect Killer* and *ProCitra-DL Botanical Crawling Insect Killer*, to control "cockroaches, spiders, crickets, millipedes, centipedes, flour beetles, cluster flies, ticks, fleas, bed bugs and Asian lady beetles on contact" in commercial and domestic environments, respectively [18]. Both products contain 10% d-limonene (technical grade), and when applied to indoor commercial facilities, they are required not to be in operation.

Second, the orange oil supply is limited and the price is increasing. This is especially true for food-grade orange oil, as obviously a biopesticide manufacturing company will not buy orange oil contaminated with synthetic pesticides.

Even though orange oil is among the cheapest essential oils, at around $10 per kilogram, its price rose from around $3 per kilogram in 2010 to around $8 per kilogram in less than a year (due to the Deep Water Horizon oil spill in the United States), and then to $15 per kilogram in 2014 due to a drop in supplies after a drought in Brazil, the main producer of orange oil. Furthermore, driven by a steady rise in the demand for "naturals," the demand for orange oil as an alternative cleaning solvent, as an aromatic flavor in food and beverages, and as a relaxing fragrance in personal care, aromatherapy, cosmetic, and perfume applications [33] is causing almost weekly price increases [34].

A manufacturer of an orange oil–based biopesticide would then ensure safe supply of the oil, including the possibility to self-extract the oil from the waste orange peel, as producers of rosemary EO as a novel food antioxidant have recently done [35]. The latter established new extraction plants in Morocco and other countries where large plantations of rosemary exist, and started to target a market dominated by manufacturers of synthetic phenolic antioxidants since the 1930s, namely, from the same years in which synthetic pesticides started to be massively used in agriculture [36].

The third reason is technical and lies in the highly volatile nature of orange oil whose components quickly evaporate. Orange oil terpenes, indeed, are not stable and are easily oxidized and deteriorated when exposed to high temperature, oxygen, and humidity [37], namely, the conditions typical of open fields. Twenty years ago, Kim and Morr were among the first to encapsulate orange oil in gum arabic microcapsules using a spray-drying technique [38]. Several other conventional encapsulation techniques have been employed, including advanced sol-gel technology for the entrapment of d-limonene in silica microcapsules [39]. However, most efforts were aimed at developing either new food or cosmetic functional ingredients.

Much room for improvement remains for the development of solid pesticides based on stable microencapsulated orange oil subject to optimized controlled release in the field environment. Indeed, whereas the open literature provides few examples of microencapsulated orange oil for pest control, several patents claim excellent pesticide properties of the microencapsulated oil. For example, applied research has shown that the efficacy of these encapsulated volatile oils increases if a nonvolatile agent is used to carry the encapsulated volatile EO [40]. Upon application to the plant or fruit, the EO and the nonvolatile agent remain in contact, the evaporation rate is reduced, and a synergestic effect enhancing the exerted protective action is observed. The Israeli company *Botanocap*, for instance, develops pesticides for crop protection with microencapsulation and slow release of essential oils based on synergistic technology [41].

15.4 Outlook and Conclusions

Looking at the future of EO-based botanicals, in 2012, Vincent and colleagues in Canada noted that "clearly, if the public wishes to have access to botanical products for home, garden, organic agriculture, or greenhouse use, then governments must be lobbied to consider reduced registration processes more seriously [6]." "Furthermore," the team insisted, "open field evaluation was needed as most research has focused on lab and greenhouse experiments."

Five years later, many things have changed. Looking at insecticide applications, it is instructive to review the feedback posted online by hundreds of customers commenting on the performance and price of one commercial orange oil–based insecticide on the website of one of the world's largest online stores [42]. Out of 339 reviews, 270 were positive and only 69 critical. The product, one customer complained, was "too expensive," being priced at $29.97 for almost 1 L. Yet, the oil not only killed ants in homes and gardens, but also effectively repelled dogs and cats, leaving a pleasant, delicate smell of oranges. "I feel much much safer this way, and my wife loves how the yard smells when I'm killing fire ants," wrote one customer.

Pointing to the practical and commercial relevance of citrus oil insecticides, in 2014 BASF entered the world's richest market, North America, with two products aimed at domestic and commercial built environments.

Even more significantly from an economic and environmental perspective is the fact that the first multipurpose biopesticide for a variety of crops entered the market, replacing several different products for pest control with a single product (PREV-AM) showing little toxicity, high efficacy, and an excellent environmental fate.

In order to make a difference, however, orange oil–based biopesticides will have to penetrate the pesticide market for crop pest control in China, Brazil, and India, namely, the world's leading agriculture countries, which, incidentally, are among the top five leading countries in the production of orange fruits.

In brief, orange essential oil will be used not only to formulate plant protection products for organic farming or for integrated pest management, but also to replace synthetic pesticide products for protecting a wide number of crops and plants in both economically developed and developing countries.

Relying on successful registration processes in Europe and North America, new and long-established chemical companies will start to manufacture large-volume products for large-scale commercial agriculture, differentiating their new environmentally friendly products via the formulation chemistry, some of which will also use nanochemistry to develop microencapsulated orange oil.

The broad spectrum of action of orange oil will also allow postharvest application of these new biopesticides, to enhance the storage of produce and valued crops, by preventing pest-induced deterioration. This, *inter alia*, will contribute to ending what Clark has rightly called a significant example of waste of our societies [43], as most waste orange peel obtained from orange juice production ends up in landfills, without extracting the valued essential oil, pectin, and hemicellulose comprising the orange peel. Providing a critical review of the scientific, economic, and environmental state of affairs, this study will hopefully accelerate this transition.

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