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Perspective on the Use of Agrivoltaic Systems for the Production of Secondary Metabolites Applicable to Food: the Case for Mint

Geanesson Alberto de Oliveira Santos¹
<https://orcid.org/0000-0003-3933-7607>

Regina Maria Matos Jorge¹
<https://orcid.org/0000-0003-3561-3555>

Fabiane Oliveira Farias¹
<https://orcid.org/0000-0002-0223-1393>

Alvaro Luiz Mathias^{1*}
<https://orcid.org/0000-0003-2536-4516>

¹Universidade Federal do Paraná – UFPR, Programa de Graduação de Engenharia de Alimentos, Departamento de Engenharia Química, Curitiba, Paraná, Brasil

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*Correspondence: mathias@ufpr.br; Tel.: +55-41-33613232 (A.L.M.).

HIGHLIGHTS

- The agrivoltaic system avoids competition for energy and food production by soils;
- Agrivoltaic system can boost the bioactive compounds production in Peppermint;
- The color of the LED determines the production of secondary metabolites in Peppermint;
- Peppermint-rich extracts give food better sensory properties and extend shelf-life;
- The addition of the plant extract prevents food waste and improves consumer health.

Abstract: Electrical energy generation through Photovoltaic Systems (PV) is a promising strategy to meet the growing demand for sustainable energy sources. However, PV creates a dilemma when considering the competition for cultivation areas with agriculture in a scenario of high need for affordable and high-quality food. On the other hand, the agrivoltaic (Agri-PV) process allows the production of electrical energy by PV, with a consortium production of at least 62% of the traditional planting. This review proposes a comprehensive analysis of trends related to the production and application of bioactive compounds, using the case of peppermint (*Mentha x piperita* L.) in an Agri-PV process with the generation of secondary metabolites as an additive for the food industry. The hybrid herb peppermint is grown through vegetative propagation using rhizomes. The location of this plant in the shading area of the PV modules is viable. It can be improved according to PV arrangements used in static or dynamic systems or internally artificially lit greenhouses. In this case, the electricity generated must illuminate with specific LEDs, control photoperiodism, nourish and hydrate the plant to avoid stress. This process makes it possible to generate

mixtures of bioactive substances, such as essential oils obtained by hydrodistillation and natural mint extract by solid-liquid extraction. These mixtures can enhance the sensory properties of juices, milk, and fruits, extend the shelf life of food products, and safeguard consumer health.

Keywords: agrivoltaic system; mint extract; mint essential oil; natural additives; food protection.

INTRODUCTION

The post-COVID-19 pandemic has driven global food inflation due to increases in energy prices, increasing poverty, and, consequently, reducing the production of goods. However, this context can stimulate agriculture and the food industry to change paradigms of generating their energy through renewable sources, such as photovoltaic (PV) energy, thus reducing the impact of prices and dependence on polluting and degrading sources [1].

Food waste reduction due to the increased shelf life of fruit, vegetables, and roots rich in starch is another important aspect aiming to minimize the energy demand and using soil and water. This measure guarantees the supply of high-quality products and facilitates the full commercialization of production, minimizing losses and maximizing the use of useful calories for family consumption, which would otherwise be wasted [2]. To illustrate, approximately 2.3 billion tons of fresh food, essential for human nutrition, are lost due to climate uncertainty, diseases, transportation inadequacies, and market demands [3]. This corresponds to about 24% of cultivated areas and 23% of global freshwater availability [4].

To contribute to generating electrical energy, PV Systems emerge as a viable and sustainable technology but compete with agriculture for land use. However, this competition is minimized when the agrivoltaic (Agri-PV) system is applied. In this case, solar energy generates electrical energy and concomitant photosynthesis for plant development through biophotonic interaction [5]. Thus, the Agri-PV system can also be used in food production and processing, such as light-emitting diodes (LED) for cultivation in controlled environments and drying [6–14].

In the first case, exposure to artificial light using LEDs in different spectrums demonstrates the potential to stimulate the production of secondary metabolites in plants, such as peppermint (*Mentha x piperita* L.); a type of Mint with high amounts of menthol. These substances have antioxidant, antimicrobial, and flavoring properties, such as terpenes and phenolics [15,16].

Secondary metabolites can be extracted by hydrodistillation (HD) to produce essential oil (EO) or by solid-liquid extraction (SLE) to produce plant extract (PE). These unit operations generate liquids containing different active biocompounds due to the peculiarities of each operation. Biocompounds can be obtained by SLE using green solvents, which guarantees food safety for consumers and environmental sustainability [17,18]. In this case, these concentrated bioactive substances make it possible to formulate edible coatings to reduce food degradation during storage, transport, and marketing. For example, leaf extracts from grumixama (*Eugenia brasiliensis*) protect fresh tomatoes. Besides, pudina, saunth, and turmeric (*Curcuma longa*) leaf extract prevents degradation of sweet lime, orange, and carrot juices, and *Mentha varidis* L. mint extract also preserves Balady orange juice [19–22]. Similarly, EO is also applicable in the agricultural industry. *Mentha Spicatta* EO that protects the degradation of "lighvan" cheese and sheep's milk, peppermint oil adsorbed by activated charcoal increases Pitaya's survival, oregano, thyme, peppermint, and lemongrass oil also increase the survival of strawberries [23–25].

This study aimed to identify the applicability of cultivating peppermint in an AGRI-PV and describe the energy used for cultivating Mint in a controlled environment with LED lamps, synthesizing its efficiency for intensifying secondary metabolites.

METHODS

Search criteria and initial records

This research has works published in journals between the years 1971 and 2024; among these, the largest concentration of works available was in the year 2023, where 75 records were selected in different databases, such as ScienceDirect, SciELO, WorldWideScience and "Periódicos Capes".

Records screening

For the searches, the following themes were used in English in the "topic" field, such as: "agrivoltaic system", "mitigation of the use of arable land", "intensification of vegetable production with different light

energies", and "green by-products for increased food quality, and survival", producing a significant number of results, around 5352 records (Figure 1).

Subsequently, it was determined that the search results should contain sub-themes as criteria for inclusion, thus establishing: 1) dual food-energy productive environment (agrivoltaic, agri-voltaic, agro-voltaic or agro-photovoltaic), 2) plant growing environment (open, closed, protected and controlled or under LED's), 3) plant cultivar (peppermint or *Mentha x piperita* L., rosemary, basil, herbaceous plants and medicinal plants), 4) metabolic enrichment secondary (plant synthesis, photosensitivity and biophotonic interaction), 5) green by-products (natural extract and essential oil and mint by-products), 6) extraction techniques (solid-liquid extraction, liquid-liquid extraction, supercritical Soxhlet extraction, hydrodistillation and steam extraction), 7) type of solvent (DES extraction, hydroalcoholic extraction and green extraction), 8) extraction of bioactive substances (extraction of biomolecules, extraction of phenolic acids and extraction of flavonoids), 9) applicability of biomolecules in foods (antioxidant activity, biosensitivity, food preservation, food protection, nutritional enrichment of foods, fruit preservation, fruit protection, juice conservation, juice protection, nutritional enrichment of juices, meat preservation, protection of meat, fish conservation and fish protection).

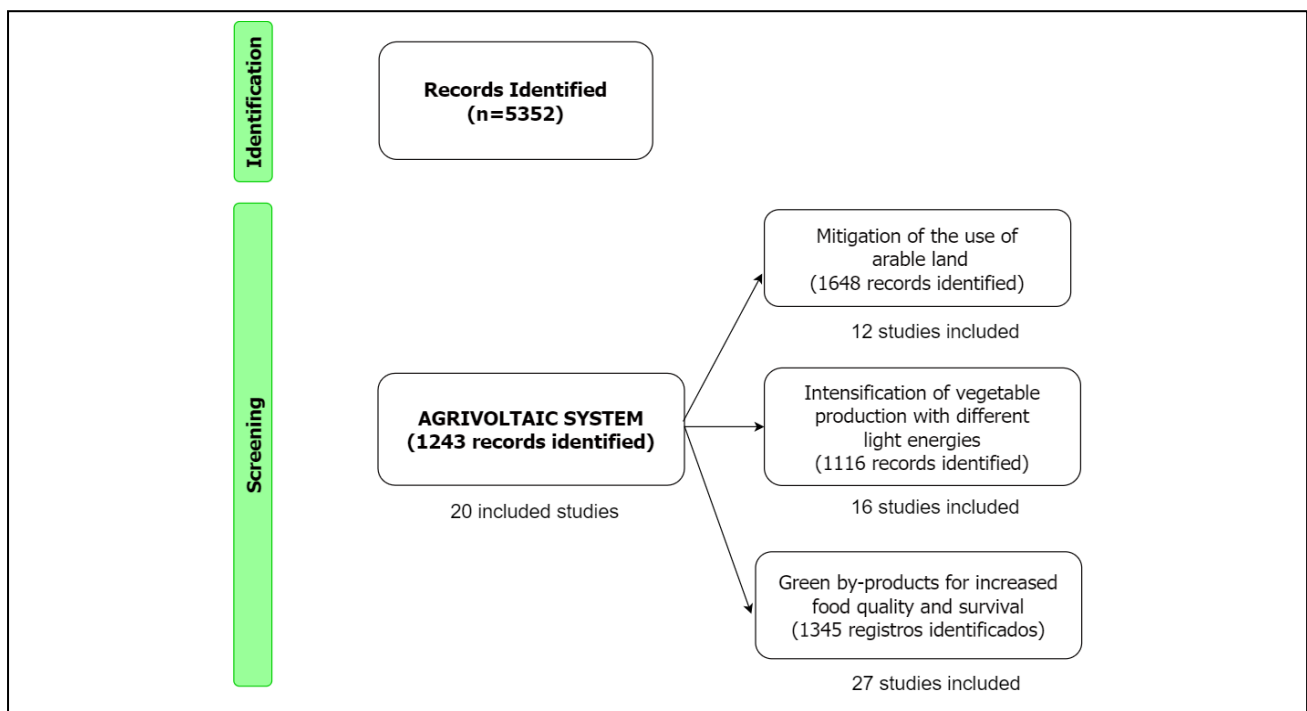


Figure 1. Diagram detailing the number of inclusion of records relevant to the search.

Synthesis of results and usage

Using Excel® software, the cited records were organized into citations, themes, and record titles. Allowing availability for consultations and analyses.

RESULTS AND DISCUSSION

Productive food-energy nexus

Contemporary society demands easily accessible, nutritious, and healthy food, which reduces productivity, increases costs, and creates unequal competition in the international market. Furthermore, climate change and its effects have contributed to food shortages by intensifying water and land competition in the agro-industry [26]. At the same time, society has a growing demand for sustainable products in managing and producing healthy foods [2]. Currently, it is estimated that around 3.5 Gt of carbon dioxide (CO₂) is emitted annually due to land preparation practices and land use changes (e.g., deforestation and degradation), contributing significantly to climate change [1, 27, 28]. Considering this, investors have considerable interest in sustainable energy generation technologies, such as cooperative agriculture production and electrical energy with photovoltaic systems (PV) [6, 7]. The PV is a set of equipment that transduces visible light energy into PV for urban, industrial, and agro-industry consumption. In this system, photovoltaic modules are composed of solid-state materials using various thin film technologies, namely,

crystalline silicon (c-Si), organic photovoltaic thin films (OPV), dye-sensitized solar cells (DSSC), concentrators for conventional opaque photovoltaic modules (CPV) and luminescent solar concentrators (LSCs). Another crucial component in this system is the inverter, which is automated equipment that converts the PV energy generated into direct current (DC) or alternating current (AC) safely applicable to the electrical connection between PV, the consumer, or, eventually, the utility [29]. PV represents three-quarters of renewable energy sources worldwide, as indicated on the International Energy Agency's (IEA) interactive map [5]. By 2030, a record installed capacity is predicted at 11,000 GW. On a regional level, Brazil's projections point to an installed generation and distribution capacity of 114.7 GW by the end of 2028, highlighting a notable growth in demand and the need for new areas to expand this type of renewable energy production. Therefore, soil competition with agriculture is inevitable [5].

Potential use of agricultural production in the field

The concept of an agrivoltaic system (Agri-PV) was introduced in 1980 [30] but was implemented in 2011 [6]. The unification of energy and food production is the trend of sustainable production, and both are dependent on climate and soil (Figure 2). The so-called agrivoltaic system [30] reduces the demand for more native land and enhances energy and food supply for global population growth. The term agrivoltaic also can be used when Agri-PV involves animal production, although it is commonly associated with plant production due to the production of plants used for food [31]. The Agri-PV system can be subdivided into three types. a) installation of photovoltaic module arrays interspersed between the crop rows; b) installation of photovoltaic modules on the crop; and c) installation of photovoltaic module arrays over cultivation greenhouses (Figure 2), what it is can be especially interesting for the use of semi-transparent/ transparent photovoltaic module. Study reports have intensified and are mainly about configuring elevations and spacing of photovoltaic modules to reduce the effects of shading on crops. In this sense, the choice of module technology, lifting height, ideal spacing, and inclination of modules must consider the highest possible energy production and minimize the impact of shading on agricultural production yield [6, 32].



Figure 2. Assembly configuration of photovoltaic module arrays for consortium production of cultivation and photovoltaic energy by the Agri-PV system, where (a) Arrays composed of photovoltaic modules interspersed between the cultivation rows; (b) Photovoltaic modules above plantations mounted on stilts; and (c) Photovoltaic modules replacing the protective covering of greenhouses or greenhouses.

Moreover, photovoltaic modules can be static or mobile. In the latter case, adjusting the inclination and orientation of the modules is done by optimizing sunlight and crop management [9, 33]. In this sense, the Agri-PV project must be based on maximizing the production of photovoltaic energy or cultivation, eventually providing the best economic profitability from the association. Logically, the suppression of solar energy caused by shading should be as relevant as possible for plant development, which is possible as plants have an intrinsic level of sensitization and light saturation beyond which photosynthesis stabilizes [34–37].

In the case of the Agri-PV system with animals, the installations of the photovoltaic modules can be static since grazing animals can also inhabit the shaded area of the photovoltaic modules, and the height must allow their free passage [1]. Raising sheep [38] and dairy cows [39, 40] are examples of success.

Agri-PV production of sheep did not harm the daily live weight gain of the animals, as the quality of the shaded forage was better and managed to compensate for the lower vegetable production than traditional production [38]. However, this is not necessarily the standard, as dry matter production from shaded forage

may be greater or lesser depending on each installation's botanical composition and soil-climatic conditions [31].

The well-being of sheep was preserved by applying Agri-PV production according to the evaluation by visual observations of the animal's behavior, such as grazing, rumination, idleness, hygiene, and animal activity [38]. Similarly, dairy cows in an Agri-PV system did not show significant changes in behavior. However, there was a lower peak of activity, which was attributed to rumination being carried out under the photovoltaic modules during the hottest period of the day [39]. The general hygiene of the herd was similar. Still, the lower body temperature of cows in the shade reveals better thermal comfort without altering milk production or its protein and fat content [40].

The shady region may be even more favorable for Agri-PV production, as for lettuce, wheat, and cucumber. These vegetables need little light from planting until the plant's pre-ripening stage. There is evidence that this type of semi-protected environment improves the resilience of crops concerning climate change.

Furthermore, agricultural production in an Agri-PV process for crops grown in uniform rows can also be advantageous, such as vines, wheat, barley, cabbage, potatoes, grapes, and oilseeds, which can be cultivated nearby and others under the shade of the modules [8, 9]. In this sense, the yield of agricultural production can be almost irrelevant—a loss of just 3% observed or relevant—up to 62% for more than 80% of the crops tested [41]. Due to this great diversity of productivity, it was not possible to create a universal model, and the configurations continue to be specific and require further studies due to the abundance of plant species and varieties of the same plant.

In this context, the assessment of the environmental impact of the support structure of photovoltaic modules, the economic implications for pumping water to support agricultural production, and the feasibility of generating electricity by small farmers in rural areas where the electricity grid [41], among others. These are other trends for developing new studies in the field, including long-term ones. Because of the shade environment produced beneath the modules, the Agri-PV system's microclimate helps reduce the interannual loss of agricultural productivity. Besides, it reduces the negative effects of frost in winter and high temperatures in summer. It even reduces the demand for water from intercropped crops [42–44], which can be an additional advantage for the demand for this input in agriculture.

The Agri-PV system has been studied to produce vegetables (62%), cereals (11%), legumes (10%), and red fruits (6%), among others (4% on grasses, 2% on oilseeds, 2% on fruit trees, 1% on vineyards, and 1% on hybrid plants). Among vegetables, lettuce is abundantly studied due to its ease of management, rapid growth, and low need for cultivation area [31], and production loss due to shading can reach 50% [45, 46]. However, an increase of 87.6% was reported despite an 18% reduction in light [47], which aligns with the complex multifactorial characteristics of the Agri-PV process. Moreover, despite the reduced lettuce mass due to shading, there are more leaves per plant. The chlorophyll content also has a complex behavior and may be slightly higher or significantly lower [31], which requires further studies.

Within this frame of reference, peppermint is an herb that can be suitably planted in an Agri-PV system.

Peppermint and green sub-products

While Mint (*Mentha × piperita* L.) is a sterile hybrid derived from a cross between *M. aquatica* L. and *M. spicata* L., rhizomes make it easier to cultivate the plant through vegetative propagation. This herb is a medicinal and aromatic plant that has antibacterial properties against Gram+ and Gram- bacteria, as well as antifungal, antiviral, antioxidant, insecticidal, larvicidal, nematocidal, allelopathic, antidiabetic, dermatoprotective, and antioxidant activities [48]. Its essential oil (EO) has the fourth-highest antimicrobial activity, surpassed only by rosemary, mustard, and sage oils [49]. Another report presents an approximate general classification (in decreasing order of antibacterial activity): oregano/clove/coriander/cinnamon > thyme > Mint > rosemary > mustard > coriander/sage [50]. Mint EO can also be used as a product deodorizer [51]. EO productivity concerning the number of leaves depends on the growing region and the season; its composition is also different. The highest production of Mint EO in the southeast region of Brazil occurred in spring (4.26%), with no difference ($p < 0.05$) between the other seasons of the year (2.30-2.86%).

The components of the EO obtained by hydrodistillation in a Clevenger apparatus for one hour were menthol and its chemical variants, and also limonene and 1,8 eucalyptol (cineole), specifically menthyl acetate (52.24-5.06%), menthone (41, 58-5.56%), menthol (41.29-16.31%), neomenthol (6.39-3.59%), isomenthone (4.51-0.66%), neomenthol acetate (4.36-0.55%), isomenthol acetate (1.67-0.26%), neoisomenthol (2.66-0.15%), menthofuran (4.13% to <0.00%), limonene (3.51-0.67%) and 1,8-cineole (4.38% to <0.01%) make up almost 100% of the oil mass [52]. Furthermore, the yield was almost quadruple the content reported for Iran [53].

Leaves, stems, flowers, seeds, roots, fruit peels, and resins can contain substances with therapeutic, odorous, flavor, and input properties for cosmetics, foods, and medicines that can be extracted and concentrated as EO (essential oil) and PE (plant extract) [54]. The product of the steam distillation or hydrodistillation operation using a Clevenger device is called EO. Yet, the products of other forms of extraction operation generate oils or emulsions with biological activities (antibacterial, antifungal, antioxidant, anti-inflammatory, cytotoxicity, etc.) applicable in agriculture, industry, medicine, etc., such as solid-liquid extraction (SLE), enfleurage, maceration, cold pressing, carbon dioxide (CO₂) and supercritical CO₂ extraction, turbo distillation, and steam distillation [55]. In this sense, solid-liquid extraction (SLE) can be an environmentally and economically viable alternative for increasing fruit shelf life, which is in great demand in the food industry. As for application, the components of EO and PE can be useful in increasing the shelf life of foods. For example, treating strawberries with thymol extends their shelf life for storage at 10°C, while menthol or eugenol also suppresses fungal growth for fewer days. These three compounds also maintained fruit quality better (higher levels of sugars, organic acids, phenolics, anthocyanins, flavonoids, and oxygen radical absorption capacity) than untreated fruits. Furthermore, PE from treated strawberries showed significantly stronger inhibition of HT-29 cell proliferation than those from control fruit [56], revealing another positive aspect.

Natural PE also contains bioactive compounds with antioxidant properties, such as phenolic compounds, flavonoids, glycosylated phenylpropanoids, and terpenoids [57, 58]. Regarding the choice of extraction solvent, the solubility of these compounds can vary greatly within the lipophilic and hydrophilic spectrums. Thus, SLE can be a suitable technique for selective extraction of more efficient components for food preservation or other applications. The SLE of these phytopathogen-inhibiting compounds can be carried out using water, organic solvents (methanol, ethanol, chloroform, and acetone), or mixtures. The use of a hydroalcoholic mixture with ethanol is very common [59], which can be attributed to the low efficiency of water to PE lipophilic substances. In this sense, some polar organic solvents (methanol, chloroform, and ethyl acetate) can better remove hydrophobic and hydrophilic molecules. Still, most are non-renewable, have high flammability and toxicity, and are not biodegradable [17, 59, 60], which prevents their use in food. Ethanol is an exception to almost all these undesirable properties, except flammability, which can be reduced when used as an aqueous mixture, including reducing the cost of the extraction solvent. Thus, hydroethanolic PE studies for food preservation are common [59]. Fundamentally, the mint-based extract potential, with menthol presence, be applicable for use as a fruit preservative, and strawberry conservation may be a good model to evaluate PE produced under different conditions.

Mint production in an Agrivoltaic system

Mint cultivation has been explored using the Agrivoltaic (Agri-PV) system. In general, plants need light to carry out their physiological processes, so Photosynthetically Active Radiation (PAR), the measure of energy incident per photon of light, from the near-infrared, 10⁻¹ eV (electron-Volts) up to a limit of 10² eV, ultraviolet, to predict flowering, photosynthesis-ripening of fruits [34-37,61]. The limitation of light availability due to shading is relevant. It cannot be neglected, which determines the arrangement of the photovoltaic modules concerning the relevant plants and the multifactorial Agri-PV.

In agriculture, growth, development, productivity, EO composition, and bioactive substances in mint plants have been improved using inorganic nutrients, biofertilizers, PGRs (plant growth regulators), and transgenic changes. The application of PGRs is effective in improving the overall performance of mint plants, both in ideal and adverse environmental conditions, as they effectively mitigate the harmful effects of various abiotic stresses by modulating the antioxidant mechanism, increasing the content of osmoprotectants, and maintaining the osmotic balance and integrity of the membrane and protein structures in mint plants. Additionally, the yield of mint plants, along with the content and composition of their EO [62], reinforces the plant physiology, which is modulated by organic and inorganic additives that influence their growth [63]. This suggests that growing with a specific substrate or using hydroponics can be effective, while avoiding unwanted abiotic effects like drought is desirable [62], which makes a greenhouse or microenvironment under photovoltaic modules of the Agri-PV system a good option.

In this manner, the comparative analysis of semi-hydroponic systems under photovoltaic modules of Mint (*Mentha arvensis* and *Mentha x piperita* L.) and basil (*Chlādek červená* and *Litrá*) revealed significant levels of nitrogenous compounds, phenolic compounds, and terpenoids. *Mentha x piperita* L. was the mint species with the best performance under low nutrient stress [58]. Regarding water stress, Mint reduced its physiological response and the content of phenolic compounds, ascorbic acid, and flavonoids, in addition to a significant increase in hydrogen peroxide and malondialdehyde (MDA) amount [64].

Intensification of secondary metabolites using light radiation from LEDs

The photovoltaic energy produced in the Agri-PV system can be stored in capacitors or shared with the local utility network, being applied for various purposes, such as general rural electrification, water supply, and dryers. It can also be used to generate light energy with LEDs for intensified cultivation [6-14, 41]. Thus, this spectral irradiance can be similar to the sun with low electrical consumption [35] of Agri-PV. This procedure can be carried out in a greenhouse with a controlled environment in an urban vertical farm format, which reduces the demand for agricultural land areas [12–14]. The use of LEDs that generate selective colors affects the plant's evolution. The wavelength of irradiation generated by LEDs affects the plant's metabolism. For example, red (660 nm) has positive effects on mint growth, while blue light (440 nm) decreases the amount of biomass generated [35].

The great advantage of the LED lighting system for Mint or plants that produce EO and natural PE is a constant luminous radiance rather. Thus, the principle of PAR must be to apply a constant Photosynthetic Photon Flux Density (PPFD) equal to natural light and with a progressive increase after some time [35], which facilitates its development [61]. Regarding the effect of the light source on the metabolism of biocompound production, *Mentha spicata* exposed separately to LEDs (blue, red, and green) concerning natural sunlight revealed that the leaves generated essential oil with carvone (80%), limonene (17 %) and other minor terpenes (3%). Green and red irradiation showed OE similar to those of control plants. Still, blue caused the complete disappearance of carvone and limonene and the simultaneous appearance of carvone oxide (65%) and eucalyptol (21%) [65]. This phenomenon was confirmed for several plants subjected to irradiation with LEDs in a controlled environment with an increase in secondary metabolites of commercial interest, such as carotenoids [64–66], phenol [64, 65, 67, 68], and anthocyanin [68]. This increase was attributed to the synergistic effects of photons with monochromatic LED wavelengths in combination with biophotonic interactions with plant photoreceptors [13, 35].

Properties of Bioactive compounds and antioxidants in Mint

Bioactive compounds can be from just one plant source or multiple sources to compose complex aromatic mixtures with different phytoconstituents, volatile or not, highlighting that EO has more volatile components than PE. However, both products can be applied for health prevention [66], e.g., mixtures with antioxidant effects. Thus, the Reactive Oxygen Species (ROS) generated in the human body by interacting its cells with atmospheric pollutants, an unbalanced diet, smoking, UV radiation, stress, and organ inflammation can be neutralized. This prevents the accumulation of unstable, negatively charged ROS molecules that oxidize quickly and form molecules derived from molecular oxygen that generate skin damage, digestive discomfort, low immunity, premature aging, cardiovascular risks, and degenerative and rheumatic diseases [67, 68]. Thus, PE must combat harmful molecular reactions in the human body, such as antioxidant, anti-inflammatory, anti-glycating, anticarcinogenic, and antimicrobial actions. For Mint, it presents substances with properties such as antipyretic, antispasmodic, analgesic, carminative, diaphoretic, antidiarrheal, and antimicrobial, as well as the treatment of irritable bowel syndrome, inflammatory bowel disease, gallbladder inflammation and dysfunction, and liver diseases [58].

Currently, the food industry is looking for solutions equivalent to the properties of PE or EO from the mint plant. For example, PE that has properties that minimize food loss [23–25]. Thus, they can be used instead of synthetic substances and are inputs for conserving products such as fruits, vegetables, meat, and fish, or even additives in juices, milk, and cheese [23]. Peppermint EO can be used as a flavoring in chewing gum, confectionery, ice cream, desserts, baked goods, tobacco, and alcoholic beverages. It is also often used in flavoring pharmaceutical and oral preparations [69]. These properties are attributed to mint biomolecules, which present hydroxyl functional groups that minimize oxidation and reduce the microbial load in fresh fruits and meats [23, 70, 71].

Many plants can produce EO and PE that can be applied to extend shelf life (due to their antioxidant and antimicrobial) and maintain food quality (Table 1). For example, thyme and oregano essential oils have bioactive compounds that efficiently inhibit fungi and the total flora of strawberries, while peppermint and lemongrass showed lower activities. Thus, they can be used to increase the shelf life of these fruits either by spraying or to create edible strawberry coatings [25]. Notably, EOs and PEs from Mint play a significant role Mint preserving fruits, cereals, and fish meat indicating a broad range of applications in the food sector. Additionally, essential oils rich in terpenes offer the potential to function as functional supplements capable of controlling lipid fractions [67]. It may be related to the wide variety of compounds that may be present but are dependent on the cultivation condition [52] and the effect of biophotonic interaction [65]. Additionally, the extraction system can be cheaper and more sustainable in the case of SLE using a hydroalcoholic solution [59].

Table 1. Concentrated and extracted green by-products for conservation, protection or functionality in food.

Green by-product	Main compound or extract portions	Function in food
Garlic EO, extracted from the bulb	Alginate (covering agent) with added EO	Increased shelf life of lamb meat after thawing [72]
EO and natural PE from multiple plants	Bioactive compounds obtained from cloves, lemon, cinnamon, lavender, oregano and peppermint	Coating on fresh edible fruits, being biodegradable based on polysaccharides to delay changes in quality [73]
EO and natural PE from multiple plants	PE such as cashew leaves, pomegranate peel, red roselle, apple fiber, and green tea extracts	Replaces chemically formulated wax coatings [73]
Peppermint EO adsorbed by activated carbon or activated carbon	Menthol (36.02%), menthone (24.56%), menthyl acetate (8.95%) and menthofuran (6.88%);	Antibacterial and antifungal activity and increased shelf life of Pitaya Dragon Fruit [24]
OE of oregano, thyme, peppermint, and lemongrass	Chitosan polysaccharides with added EO	Antimicrobial action and protection to increase the shelf life of strawberries [25]
Fennel seed extract	Rutin, quercetin, apigenin, phenolics (chlorogenic acid, caffeic acid and 1,5- dicaffeoylquinic acid)	Increased shelf life of yogurts, doses not exceeding 1% [74]
Combination of ingredients pomegranate, rosemary, hydroxytyrosol, and citrus fruits in the form of PE	Pomegranate (41.4% punicalagin), rosemary (5.8% carnosic acid and carnosol), hydroxytyrosol (7.3%) and citrus fruits (55% hesperidin) combined separately with acerola (17% vitamin C) and oil essences rich in fatty acids (45% α -linolenic and 40% docosahexaenoic)	Natural substitute for synthetic preservatives for fish patties [71]
Mint extract <i>Mentha piperita</i> L.	Diglucoside flavonoids and oxime derivatives	Protect cereals against infection by <i>P. sorguina</i> and <i>F. moniliforme</i> [16]
Natural pudina, saunth, and haldi extract	Compounds, tannins, flavonoids, coumarins, thiosulfinates, glucosinolates, and saponins, isolated from these plants are secondary metabolites responsible for plants' antimicrobial action and medicinal properties.	Antimicrobial activity, increased shelf life of sweet lime, orange and carrot fruit juices [20]
Extract of mint leaves, citrus fruits, and peels	The mint leaf extract showed a higher amount of phenolics and higher in vitro antioxidant activities than the citrus peel extract.	Antimicrobial action, increased shelf life of mackerel fish [75]
Extract of mint leaves and cumin seeds.	The antioxidant properties of Cumin wild mint seeds and leaf extracts are related to phenolic, γ -terpinene compounds and monoterpene components.	Antioxidant and antimicrobial action, rainbow trout fish fillet [21]

CONCLUSION

Food safety requirements and environmental sustainability must align with the traditional demands for high-quality and affordable food. Additionally, the growing population's increasing energy needs create competition between agricultural production and photovoltaic energy generation. In this way, the agrivoltaic system (Agri-PV) can mitigate much of this conflict, maintaining part of the agricultural or animal production with agricultural production between or under the plates in static or dynamic systems, as well as over greenhouses. In the latter case, ideally using semi-transparent plates. Agri-PV allows the production of up to 62% of the traditional cultivation of most crops and can also be beneficial for livestock farming. To this end, Agri-PV optimization studies are essential to define the design of plate implementation, and cultivars and varieties of production entities, particularly the multifactorial conditions of these productions. Electrical energy from Agri-PV can be inserted into the grid or used for the property's various energy demands, but also for special applications, such as photostimulation of plants to produce secondary metabolites of commercial interest.

For example, *Mentha x piperita* L. can be cultivated in the Agri-PV system and is rich in secondary compounds with bioactivity through hydrodistillation (HD) or solid-liquid extraction (SLE). In this context, several plants can produce essential oils (EO), generally obtained by HD, or plant extracts (PE), generally obtained by SLE. Hydrodistillation demands more energy and always produces the same qualitative-quantitative set of biocompounds. In comparison, liquid-solid extraction uses less energy and can produce different quantitative compositions of PE due to the different interactions created with different solvents. Therefore, using a hydroalcoholic solution with a specific ethanol concentration may be the best option due to the desired PE component standard. It is also for environmental sustainability and use in food due to its low toxicity.

Additionally, Agri-PV energy can be used for photostimulation. Therefore, growing Mint with photoperiod intensification with LED lighting of a specific color can enhance the production of its desired secondary metabolites, especially in a greenhouse environment. Additionally, the semi-hydroponic system can be palliated to minimize water stress and possibly inadequate saline concentration in the soil.

As for commercial potential, mint extracts can be applied to maintain or even improve foods: increase shelf life (yogurt, juices, and lamb meat), replace synthetic preservatives (fruits and meats), replace wax coatings (fruits), promote antimicrobial activity (cereals, juices), act as an antioxidant and antimicrobial agent in a wide variety of foods (pitaya, strawberries, rainbow trout, and mackerel). Thus, Mint can be a success story by taking advantage of the use of the same soil to produce photovoltaic energy. This case is just an example of the full potential of photostimulation, whether with Agri-PV energy or not.

Food safety requirements and environmental sustainability must align with the traditional demands for high-quality and affordable food. Additionally, the growing population's increasing energy needs create competition between agricultural production and photovoltaic energy generation. The agrivoltaic system (Agri-PV) can mitigate much of this conflict by maintaining part of the agricultural or animal production alongside photovoltaic panels in static or dynamic systems and over greenhouses, ideally using semi-transparent panels. Agri-PV allows for up to 62% of the traditional cultivation of most crops and can also benefit livestock farming. Therefore, optimization studies are essential to define the design of panel implementation and the selection of suitable cultivars and production varieties, particularly considering the multifactorial conditions of these productions. Electrical energy from Agri-PV can be integrated into the grid or used to meet various on-site energy demands, including special applications such as the photostimulation of plants to produce secondary metabolites of commercial interest.

For example, *Mentha x piperita* L. can be cultivated within the Agri-PV system, producing bioactive secondary compounds through hydrodistillation (HD) or solid-liquid extraction (SLE). Various plants can produce essential oils (EOs), typically obtained by HD, or plant extracts (PEs), generally obtained by SLE. Hydrodistillation demands more energy and consistently produces the same qualitative-quantitative set of biocompounds. SLE, in turn, uses less energy and can yield different quantitative compositions of PEs based on the solvents used. A hydroalcoholic solution with a specific ethanol concentration may be optimal for producing desired PE components, enhancing environmental sustainability and food safety due to ethanol's low toxicity.

Moreover, Agri-PV energy can be used for photostimulation. Cultivating Mint with photoperiod intensification using LED lighting of specific colors can enhance the production of desired secondary metabolites, especially in a greenhouse environment. Additionally, a semi-hydroponic system can mitigate water stress and manage saline concentrations in the soil.

From a commercial perspective, mint extracts can be used to maintain or even improve food quality: extending shelf life (e.g., in yogurt, juices, and lamb meat), replacing synthetic preservatives (in fruits and

meats), substituting wax coatings (on fruits), promoting antimicrobial activity (in cereals and juices), and serving as antioxidant and antimicrobial agents in a wide variety of foods (e.g., pitaya, strawberries, rainbow trout, and mackerel). Thus, mint cultivation exemplifies the potential of utilizing the same land for agricultural and photovoltaic energy production. This case illustrates the broader potential of photostimulation, whether powered by Agri-PV energy or other sources.

In this context, several plants can produce essential oils (EO), generally obtained by hydrodistillation, or plant extracts (PE), generally obtained by solid-liquid extraction. In the latter case, without great energy demand and the possibility of producing different quantitative compositions resulting from the interaction with different solvents. The hydroalcoholic solution with a specific ethanol concentration may be the best option due to environmental sustainability and use in food.

Mentha x piperita L. mint is rich in EO, has bioactive components in its EO or PE, and can be grown in an Agri-PV system. Cultivation of Mint with photoperiod intensification with color-specific LED lighting can enhance the production of its secondary metabolites. The controlled greenhouse environment can select the desirable composition of bioactive compounds..

Mint extracts can be applied to maintain or even improve foods: increase shelf life (Yogurt, juices, and lamb meat), replace synthetic preservatives (fruits and meats), replace wax coatings (fruits), promote antimicrobial activity (cereals, juices), act as an antioxidant, antimicrobial agent in a wide range of foods (Pitaya Dragon fruit, strawberries, rainbow trout fish and mackerel fish). Thus, Mint can be a success story for taking advantage of using the same soil to produce photovoltaic energy.

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