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Review

Exploring the Multifaceted Aspects of Strawberry Tree (*Arbutus unedo* L.) Forests in Portugal

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Abstract: This article explores the ecological role of strawberry tree forests (*Arbutus unedo* L.) in the resilience of Portuguese forest ecosystems and their relationship with plant production as a source of food. It discusses the importance of the strawberry tree in fire combat and the improvement of agroforestry areas by mitigating erosion and augmenting soil organic matter. The multifunctionality of their fruits, emphasizing their utilization in food and beverage production, is also addressed. Moreover, the socio-economic and cultural significance of fruit production, emphasizing its role in sustainable development, is analyzed. The diversity of beverages (spirits, liquors, and gin) and food products (jams, jellies, etc.) effectively contribute to have a positive social and economic impact on the local populations and tradition maintenance. Moreover, the bioactive compounds in different parts of the plants and fruits have applications in pharmacology and cosmetics. Finally, the valorization of strawberry tree spirits mush waste as a source of natural dyes for textiles is discussed as a promising research topic to be explored in the future.

Keywords: *Arbutus unedo* L.; agrifood applications; local community benefits; ecological resilience; pharmaceutical applications; waste valorization

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1. Introduction

Arbutus unedo L. (strawberry tree) is an Ericaceae that belongs to the genus *Arbutus* and is a native Mediterranean–Atlantic species, distributed throughout the Iberian Peninsula, western and southern Europe, the Middle East, and northern Africa (Figure 1), where it grows spontaneously in drained and dry soils and rocky areas [1,2]. The strawberry tree is a shrub or small tree whose height does not usually exceed 5 to 12 m.

In Portugal, some authors have referred to it as a neglected or underutilized crop species (NUC). This classification gives the strawberry tree agricultural interest and agroindustrial potential, especially for the populations living in rural areas where it is native, but which, for several reasons, is not fully utilized [3,4].

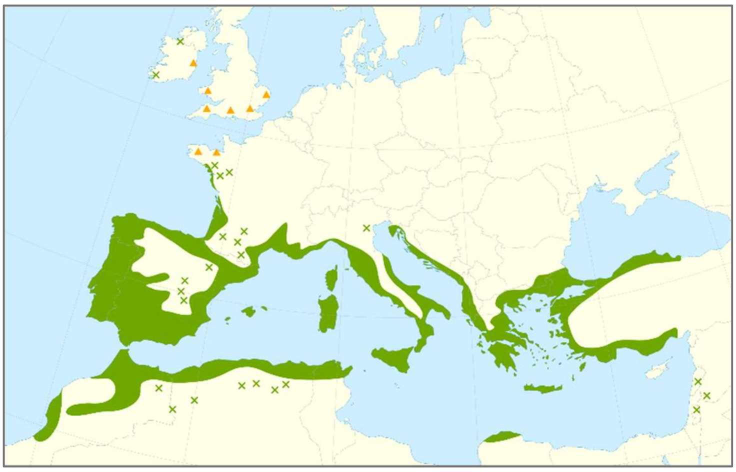

Figure 1. Chorological map of the strawberry tree (*Arbutus unedo* L.). The distribution ranges of the species' native populations are shown in green. Isolated populations and introduced and naturalized areas (synanthropic) are shown as point features and appear on the map as green crosses and orange triangles, respectively (Global Facilitation Unit for Underutilized Species—GFU [5]; last update: 18 May 2018).

In Portugal, it is widespread throughout the mainland, from Trás-os-Montes to the Algarve, as illustrated in Figure 2, occupying around 15,500 ha [6].

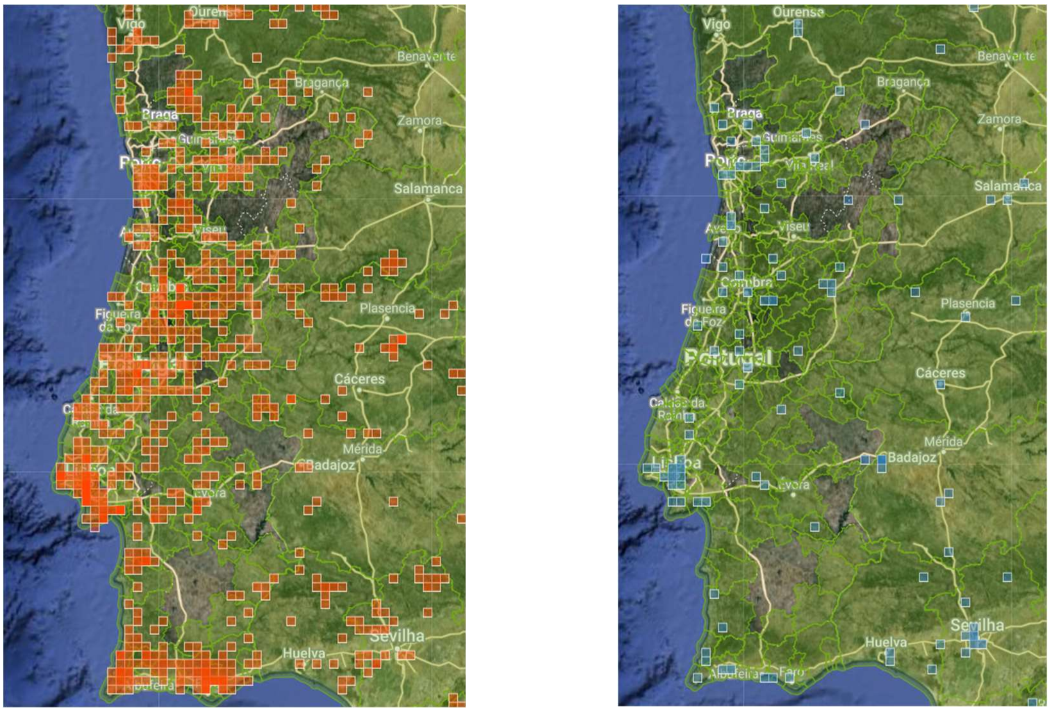

Figure 2. Portugal map with the distribution of the strawberry tree (*Arbutus unedo* L.): on the left, the orange squares represent the verifiable observations of trees, and on the right, the blue squares represent cultivated trees.

In Trás-os-Montes [7], the species grows in *Quercus* and *Pinus* forests with a very fragmented distribution due to afforestation programs and low temperatures. In the Algarve region, the strawberry tree is found spontaneously in the north and west sides of the Serra de Monchique and in the Serra do Caldeirão. It is the fourth most representative species in the Algarve, found in about 13% of the soil of the region, corresponding to an area of 12,110 ha (information from The Regional Spatial Plan for the Algarve, approved in 2007) [8].

Afforestation and reforestation efforts can play a dual role in enhancing wild spaces and restoring degraded ecosystems. In 2020, the authority to approve such activities involving specific forest species was decentralized to the municipalities within the respective territorial jurisdictions, provided they had a dedicated forestry office (Decree-Law No. 32/2020 of 1 July). Data from the Institute for the Conservation of Nature and Forests I.P. revealed a significant increase in the authorization requests for planting strawberry trees, with favorable opinions issued by the technicians from the Regional Department for Forest Management and Enhancement—Algarve, particularly in January 2024 (56.70 ha) compared to the previous two years (13.87 ha in 2023 and 14.99 ha in 2022). Most of these requests were part of mixed planting projects involving strawberry trees and cork oaks or included the cultivation of strawberry trees in areas where other species already exist. This recent surge in authorization requests suggests a positive shift in the perception of the strawberry tree as a valuable species, particularly in the Algarve region.

The strawberry tree normally grows in a shrub-like form with upright branches that grow from the trunk 0.50 m above the ground and are also widely spaced, and generally reach an average height of around 4–5 m, depending on the environment (bushes vs. trees), but which, in conditions of greater competition for light, can reach up to 12 m. The crown is rounded with elliptical evergreen leaves that are dark green in color, with a waxy sheen on the upper surface. The white, or slightly pink, flowers that appear in clusters in autumn and early winter on the tree are very decorative, and for this reason, it is considered an ornamental plant. The flowers are hermaphrodite, arranged in terminal panicles of 15 to 30 flowers. The species' hermaphrodite blossoms are self-fertile; however, the entomophilous pollination of the flowers improves fruit production and fruit size. The insects best suited to start the pollination of the flowers of the strawberry tree are those of the genus Bombus (commonly known as bumblebees), as they are bigger than bees, and open the entrance of the little flowers to bees (Figure 3 [9]). During the fall and winter months, the species' hermaphrodite blossoms, due to their melliferous traits, are the main source of food for bees [10,11].

Figure 3. Strawberry tree orchard located in the central region. Flowers and entomophilous pollination. Source: Estevão (2023) [9].

The strawberry tree also produces edible fruit that are spherical and fleshy, with seeds covered by numerous pyramidal projections.

The strawberry tree is a plant with a very long cycle for the fruit development process; from the flowering to harvesting of the fruits takes a period of one year (Figure 4). It has four distinct phases: flower bud initiation/flowering, fruiting, ripening and harvesting. The long period (1 year) from pollination to fruit ripening (fall to the following fall) characterizes the risk associated with fruit production, due to precipitation, wind, frost, and drought. This cycle starts with the formation of the flower buds in June and finishes with the ripening of the fruit, which takes place between October and December of the next year. It should also be mentioned that this crop has flowers and fruits on the tree simultaneously, which also constitutes an important restriction for the mechanization of fruit harvesting, in order to not compromise the following year's production.

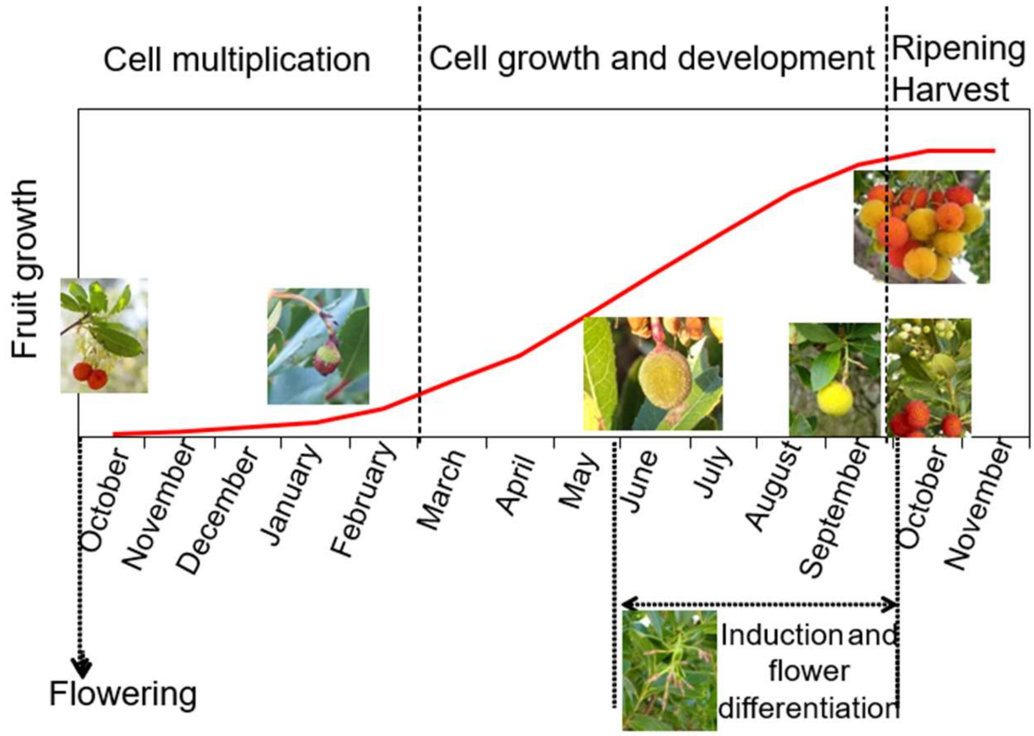

Figure 4. Illustration of strawberry tree fruit growth (adapted from Franco (2013) [12]).

During the ripening process, the fruit changes color from green to yellow, orange, and finally red when ripe, as shown in Figure 5. Depending on its destination, the fruit is usually harvested before it is fully ripe, when it should be yellow to orange red. Usually it takes place from September to December, depending on the region where it grows and the weather conditions each year. It requires several passes, and the color of the fruit is the best parameter for determining the time of harvest, as it is closely related to firmness, which is more difficult for producers to determine [13].

Figure 5. Change in the color of the strawberry tree fruit as it ripens (adapted from Gomes et al. (2019) [13]).

The strawberry tree is highly valued in the southern and central regions of Portugal, where it is used to make liqueurs, such as "*licor de medronho*", and distilled drinks, such as spirits (traditional and relevant production) and gin (more recent and lower production), playing important social and economic roles since part of the local population depends on this activity. According to the data from the 2019 Agriculture Census, there are 2855 strawberry trees on individual farms in mainland Portugal, with an area of 9830 ha. About 25% of the trees are for fresh fruit production, and the remaining strawberry tree fruits are dedicated to spirit production, known as "*aguardente de medronho*". The Algarve region has the most impressive area, with about 7200 ha, which correspond to 73% of the total surface occupied by strawberry trees, and 92% of this area is dedicated to "*aguardente de medronho*" [14]. Recently, several other applications beyond the more traditional ones have become common. The fruits are used in the food industry as raw materials for sweets, ice creams, jams, and confectionery products, such as jellies (*pâté de fruits*) and liqueur bonbons. Additionally, ripe fruits are suitable to be frozen, dehydrated, or freeze-dried.

Furthermore, aside from its evident potential for economic development, it is important to highlight that Arbutus is a multifunctional species with various applications in different industrial sectors [4]. For instance, it has been researched as a source of functional compounds and fibers [15] for industries, such as pharmaceuticals [16–20], cosmetics [21,22], and food [23–28]. Additionally, its ornamental value is significant, owing to its prolonged flowering season and attractive fruits, making it an appealing choice for landscaping. Moreover, Arbutus holds promise as a species conducive to beekeeping. Furthermore, it plays a crucial role in forest management, contributing to the composition of forest ecosystems and serving as a natural barrier against forest fires in primary and secondary networks. In parallel, it aids in the enhancement of agroforestry areas by mitigating erosion and augmenting soil organic matter.

For all these reasons, the fruits of *Arbutus unedo* L. have several food applications and beneficial properties for human health, making them economically valuable in rural areas [29]. Additionally, the species has a high ornamental, environmental, and medicinal value, and is widely used by foresters, farmers, and rural populations.

In Portugal and other Mediterranean countries, *Arbutus unedo* L. has an ecological and putative socio-economic impact, and efforts are being made to assess its genetic diversity for breeding and conservation purposes [30,31]. Overall, *Arbutus unedo* L. has both social and economic significance due to its food industry applications.

2. Ecological Role in the Resilience of Forest Ecosystems and Its Relationship with Plant Production

The ecological role of the species is interrelated with its climatic tolerance (hydric stress and frost resistance), type of parent material restrictions (siliceous, schist, and limestone), soil conditions (depth and availability of nutrients and water), and regeneration ability (vegetative and seed regeneration). The species of the Arbutoideae subfamily are drought stress-tolerant, showing characteristics of the sclerophyllous taxa (small, thick, and waxy leaves to reduce water loss by evapotranspiration), mainly of the western North American species [32]. However, the four species of *Arbutus* in the Mediterranean region (South Europe, North Africa, and the Middle East) do not show such high hydric tolerance. These comprise *A. unedo*, *A. andrachne*, *A.* x *andrachnoides* (*A. unedo* X *A. andrachne* hybrid), and *A. canariensis* (from the Macaronesia region). The strawberry tree has laurel-like leaves that are evergreen, wide, and adapted to high temperatures and a humid atmosphere (Figure 6), unlike the cork oak and holm oak, dominant trees in the south of the country, which also have evergreen leaves; however, they are narrow and adapted to both dryness and frost, characteristics of the sclerophyllous taxa [13].

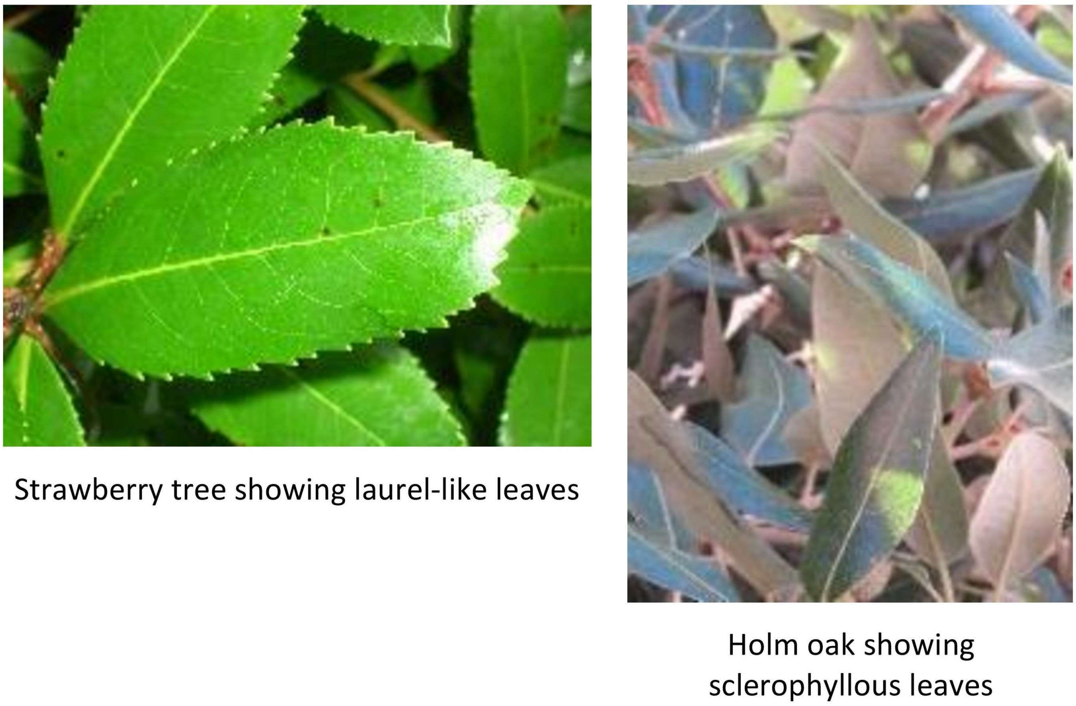

Figure 6. Strawberry tree (**left**) with laurel-like leaves denoting inferior resistance to drought stress when compared to Holm oak (**right**) with sclerophyllous leaves (adapted from Gomes et al. (2019) [13]).

As a result of the above characteristics, *A. unedo* proliferates in mild regions, characterized by neither very dry summers nor freezing winters, that is, coastland and inland regions showing a maritime influence [1], accordingly, the Mediterranean laurel-like vegetation [6]. So, the strawberry tree does not tolerate very dry summers (annual rainfall below 550 mm) unless it is installed close to watercourses or groundwater and is normally excluded from higher altitudes (around 900 m altitude) with more frequent and prolonged periods of frost; these are the main restrictions on the distribution of the species in Portugal [13].

Regarding the parent material, the strawberry tree adapts to different types of materials originating from the soil (granite, schist, sand, and limestone), preferring silicon or decarbonated soils [6], and growing in relatively acidic to alkaline soils, between 5 and 7.2 pH [33].

The strawberry tree grows better in soils of moderate depth (Cambisols) than in shallow soils (less than 25 cm, Leptosols) typical of forest areas. Nevertheless, in shallow soils with low fertility, the species grows similarly to other low shrubs, showing the ability to recover degraded soils [13,34]. Moreover, the species' nutrient requirements are inferior when compared to those of other fruit trees, showing a pioneer status as well [35–37]. These characteristics of the species have become increasingly valued, particularly for the recovery of degraded soils and abandoned farmland [34,35].

However, the strawberry tree maintains a typical characteristic of the sclerophyte taxa, that is, its resistance to forest fires. In this case, it is not due to the seed's tolerance to high temperatures, nor to the thickness of the bark to protect the cambium, but rather due to its ability to sprout from the meristem in the stem and roots through lignotubers, even when the entire crown is affected (Figure 7). In this case, the main strategy for surviving forest fires is associated with the meristem's presence in the wood's lignotubers [38,39].

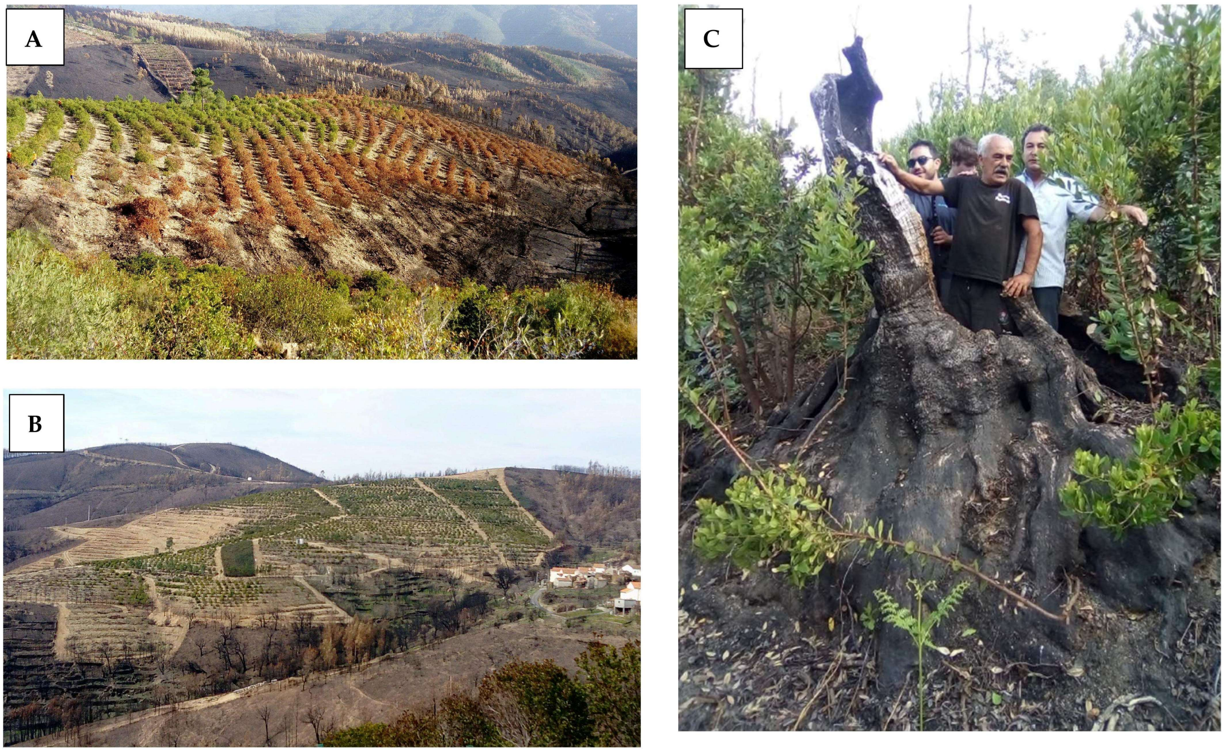

Figure 7. After a severe fire in 2017 in the central region, the strawberry tree orchards in the mountain regions showed their firebreaking ability (**A**), particularly relevant near villages (**B**), and also showed resistance to forest fires due to their ability to sprout from the meristem in lignotubers. (**C**) More than 6 people could fit inside the burnt stump created by the action of the fire, and after 4 years, in June 2021, it already showed fruit (adapted from Gomes et al. (2019) [13]; courtesy of João Pedro Borges, Barriosa, Seia, Portugal (http://www1.esac.pt/medronho/Noticias.html, accessed on 12 November 2024).

In the Mediterranean Basin, two main elements, drought and forest fires, are responsible for the vegetation dynamics. Although tree mortality is generally linked to fire severity, the softwood is severely affected, while the hardwood is more resistant, depending on the thickness of the bark and the tree size, which are linked to the reserves of carbohydrates in the trunk and in the roots (equivalent to trunk dimension) able to support successive sprouting and regrowing [40].

Considering *A. unedo*'s fire resistance and resilience in shallow, nutrient-poor soils, this is a species that needs to be preserved, as it can prevent desertification and support the fauna in general and, in particular, birds, insects, and bees [7,41,42]. Thus, it contributes to the preservation of biodiversity, the increase in soil organic matter, water retention, the biological activity of soils, and consequently the stabilization of soils and the recovery of degraded soils [6,41]. Vegetation regrowth varies, depending on a fire's intensity (Figure 7). The resilience of the strawberry tree to fires is remarkable and is associated with its ability to regenerate even after more intense forest fires, sprouting from the stump as shown in Figure 7, or from the main trunk in less intense fires.

This characteristic is also observed in *Erica arborea* [43]. Furthermore, its use, particularly in the central and northern regions of Portugal, with pine and eucalyptus monocultures creates a discontinuity in the forest biomass, reducing the risk of fire, its spread, and its intensity [44]. Fire resistance makes it relevant for reforestation programs, creating buffer zones, such as agroforestry systems, and reducing the risk of fires spreading [34,44]. According to [45], new fire prevention strategies are needed to protect villages, especially at the forest–village zone interface, due to the increasing occurrence of high-intensity fires in the Mediterranean region. The authors used a combination of different meteorological conditions (standard vs. extreme), buffer zone areas (distances of 100 m vs. 500 m), and different land covers to evaluate fire behavior. They demonstrated that the establishment of deciduous forests and wider buffer zones can reduce the intensity of a fire line by up to five times.

Furthermore, in extreme weather conditions, the flame length is substantially reduced, reaching just 0.8 m under standard weather conditions. Among other broadleaves, due to its rusticity, namely, its ability to adapt to degraded soils, shallow soils (Leptosols), and low fertility, *Arbutus* may play an important role in buffer zones, mainly in the wildland–urban interface, particularly in mountainous regions. *Arbutus* offers interesting economic and ecological value for firebreaking purposes. Different goals, such as environmental restoration, firebreaking, and orchard establishment for fruit production, can be achieved considering *A. unedo's* plasticity to different environments and its large morphological and phenological range, which allows for the accession selection accordingly [33,35]. However, not long ago, for plant production, seeds were extracted from the fruits of native plants, without concerns about their productivity or fruit quality [7,33,46,47]. But recently, for the establishment of orchards for fruit production, *A. unedo* has been seen as a wild fruit species, which has increased the demand for high-quality plant material by forest owners [2,33,35].

Chá and coauthors [48] found a significant relationship between the sugar content and climatic classification by the xerothermic index in a study that included 204 strawberry tree accessions located from the north to south of Portugal. The authors found that the lowest sugar contents were linked to the lowest and the highest values of the xerothermic index. In the first case, notwithstanding soil water availability in the north, the lowest temperature and photoperiod induced a reduction in photosynthesis, mainly during fruit ripening (autumn, Figure 4). In the second case, low soil water availability, associated with limestone zones (disposed to water retention), induced a reduction in photosynthesis, mainly during the active fruit growth period (Figure 4). This achievement demonstrates the relevance of breeding programs for a better understanding of this species and for providing guidance on the implementation of new, more adaptable and productive orchards, especially to produce distilled spirits, the main current source of income.

In an ongoing improvement program, adult plants were examined in different regions of Portugal for their fruit quality and productivity, and the best ones were micropropagated [3]. Next, field trials comprising clonal plants and seedlings were established in diverse ecological conditions to study the interaction between the genotype and environment (Figure 8). To compare the distillates' composition between those issued from clonal plants and seedlings, the distillates obtained from their fermented fruits were analyzed [49]. The results showed that the volatile profile of each sample (fifteen fruit distillates) was more associated with the alcoholic fermentation process, dependent on the native microbiota, than with the plant's origin (clonal x seedling).

Population genetic studies have been performed using several molecular markers [15,50]. The main goal of the improvement program was not only to propagate the best adult plants more adapted to the climatic and soil conditions, but also to conserve the most diverse (in situ or ex situ). The use of molecular markers allows for the establishment of genotype fingerprints as a useful technique to assure the highest genetic biodiversity, whether for the implementation of orchards for seed production or for ex situ genetic resources conservation [51]. In Portugal, around 21.5% of the territory is included in Classified Areas (https://dre.pt/web/guest/legislacao-consolidada/-/lc/114449631/201608120100/73511679/diploma/indice, accessed on 4 October 2024), which include protected areas (https://www.icnf.pt/oquefazemos/materiaisinformativoseeducativos/areasprotegidas, accessed on 4 October 2024) and areas integrated into the Natura 2000 Network (https://www.icnf.pt/conservacao/redenatura2000, accessed on 4 October 2024). In these areas, there are management restrictions depending on the protection status. Within the scope of these restrictions, regeneration with seedlings whose seeds do not come from the same area of origin is not allowed. These restrictions aim to conserve habitats by allowing for forest genetic resources' in situ conservation. In Portugal, there is an in situ conservation area of Arbutus unedo in the central region (Mata do Sobral) under government management (ICNF). In the set of 204 strawberry tree accessions characterized by Chá and his team [48], 50 of them were included in an ex situ reserve, according to their agronomic characteristics and genetic diversity.

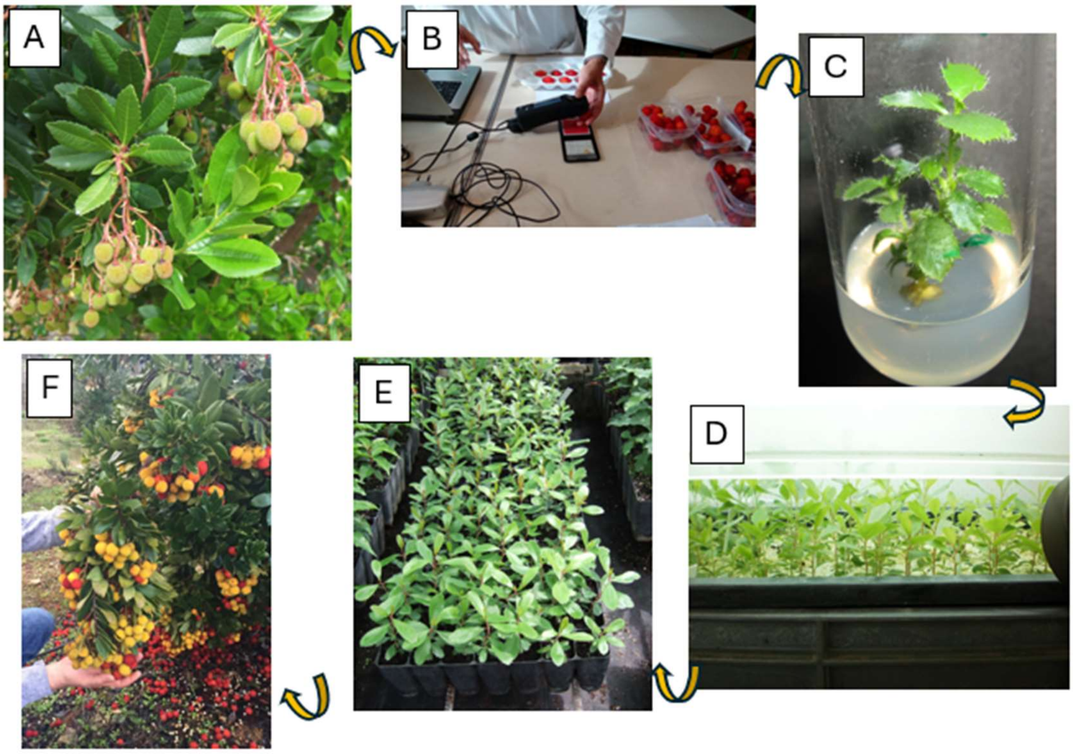

Figure 8. Micropropagation of selected adult plants (**A**) according to fruit production and quality analysis (**B**). After establishment in vitro, shoots multiplication (**C**), ex vitro rooting, and acclimatization (**D**), plants were transferred to nursery conditions (**E**) to establish field trials in different ecological conditions (**F**) (adapted from Gomes et al. (2019) [13] and courtesy of T. Cristóvão and J.P. Dias, Proença-a-Nova Clonal Orchard (http://www1.esac.pt/medronho/divulgacao.html, accessed on 12 November 2024), IV Encontro do Medronho, Signo Samo, 2021).

In addition to the previous aspects, plant productivity depends on the nutrient dynamics in the soil–plant system. Soil nutrients, organic layers, leaves, and fruit analyses must be accomplished. Pato and coauthors [35] showed the relevance of a rational fertilization program for efficient nutrient uptake by plants to enhance fruit production and quality. Their results showed that fruit production and quality are dependent on the vegetal material (selected clones according to the ecological conditions), fertilization, conservation of the soil organic layers (no soil mobilization), and mulching techniques.

Arbutus unedo forms arbutoid mycorrhizae with a variety of Ascomycetes and Basidiomycetes, being generally a host of ectomycorrhizal fungi [52]. Richard and coauthors [53] found the high species diversity of the ectomycorrhizal fungi community (ECM) growing in the natural forest areas of *Quercus ilex* and *Arbutus unedo* in the Mediterranean region. Both species share about 15% of the ECM, with *Cenococcum geophilum* being the dominant species (35% of the ECM). The ECM plays a significant role in enriching organic matter, stabilizing the soil (formation of clay–humic aggregates), and consequently mitigating soil erosion. Furthermore, it contributes to carbon and water retention, as well as a forest that is more resilient to water stress, nutritional requirements, and plant health [54]. Mycorrhizae growing under natural conditions opens new opportunities to produce biological inoculants, especially for enhancing the recovery of forestry agrosystems and providing another source of income. In the case of the genus *Tuber*, the ability to form *Arbutoid mycorrhizae* with *Arbutus unedo* seems like a common characteristic. Thus, there is another relevant economic opportunity for *Arbutus* in the Mediterranean region, particularly in mountainous areas, using plants inoculated with the *Tuber* species or *Lactarius deliciosus* [52,55–57]. The combination of high-quality fruits, honey, and edible mushrooms could diversify and increase incomes, encouraging buffer zones' expansion for wildfire prevention, both at the forest–urban interface and in mountainous areas [56].

3. The Duality: Food and Beverage Production with Local Social Benefits

The strawberry tree fruit, known in Portuguese as "*medronho*", is composed of a multitude of compounds with great nutritional quality, including sugars, proteins, phenolic compounds, organic acids, unsaturated fatty acids, fiber, vitamins, and carotenoids [26]. The fruit, in its unripe and ripe stages, has the following range of sugars (on a dry basis), respectively: fructose (2.33–20.8%), glucose (3.95–12.5%), and sucrose (8.77–8.68%) [58]. It is rich in minerals, such as potassium, calcium, phosphorus, magnesium, and sodium, [59,60]; vitamins C and E [61]; carotenoids; and antioxidants.

The energy value of strawberry tree fruits is high due to their high sugar content. They also have a high content of fiber, both soluble and insoluble, with pectin being the most important [25]. The presence of polyphenolic compounds, namely anthocyanins, phenolic acids, flavonoids, gallic acid derivatives, catechuic tannins, coumarins, quinones, and anthraquinones, characterized by their high antioxidant potential [26,62], is responsible for many of the biological functions recognized by the strawberry tree fruit's consumption [63–67].

For the above reasons, strawberry tree fruit is rich in bioactive ingredients, such as polyphenolic compounds and dietary fiber, which have a beneficial impact on human health. The food industry is therefore looking for new ingredients to enhance existing products. Strawberry tree fruit, with its chemical composition and bioactive compounds, should be seen as an interesting ingredient for the expansion and development of new functional products [25].

Traditionally, most of the ripe strawberry tree fruits are harvested and fermented to produce spirits, a distilled alcoholic beverage with a high alcohol content (45–50% ethanol, v/v) [68]. Spirit production is the most economically significant form of its exploitation [3]. The composition of the distillate varies greatly throughout the distillation process [69,70], and therefore, the use of correct distillation technology, separating the different distillation fractions, is considered good practice [71] for obtaining quality brandy. The ripeness of the fruits [72], as well as the biological variability among the plants used to produce arbutus berries [49], the addition of water to the fruits before fermentation [69], and the activity of the autochthonous microbiota, especially the yeast present in the fruits, influence the composition and the distillate's sensory qualities [73]. In fact, a study of the spontaneous fermentation of strawberry tree fruit from different producers in the center of Portugal concluded that there was a high variety of indigenous *Saccharomyces cerevisiae* yeasts, which could be separated into eight clusters, responsible for the distinct physicochemical and volatile composition of the distillates produced, which could be associated with each producer [73].

To minimize the potential risk of the presence of methanol in distilled spirits beverages produced during the spontaneous and uncontrolled fermentation of strawberry tree fruit, Anjos and their coworkers [74] developed a new spirit drink mixing honey with strawberry fruit, and concluded that the methanol level in the new spirit was significantly lower compared to arbutus spirit. Methanol results from the activity of the pectin methylesterases, which removes the methyl side chains of pectin, a natural component of strawberry tree fruits during ripening and fermentation [75]. In addition, the fruit can be consumed fresh or traditionally processed into jams and jellies.

The fruit of the strawberry tree is highly perishable. Domingues and his team [29] evaluated the physicochemical and microbiological parameters of strawberry tree fruit stored for 0, 4, 11, and 21 days at room temperature, under refrigeration, and by freezing. They observed that the most common microbiota in the fresh fruits were psychrotrophs (4.07 ± 0.25 log CFU/g), yeasts (3.39 ± 0.18 log CFU/g), mesophiles (3.26 ± 1.20 log CFU/g), and molds (2.70 ± 0.55 log CFU/g). After 11 days of storage, the microbial content increased from 66 to 116% at 25 ± 1 °C, while at 6.5 ± 1 °C, the growth ranged from 3 to 53%. The molds constituted an exception, since the number decreased under those conditions. Storage at freezing temperature for 21 days revealed a slight increase in the psychrotrophs and yeasts. *Rhizopus stolonifer*, *Aspergillus carbonarius*, and *Penicillium brevicompactum* were the most frequently identified molds, and for the yeasts were *Aureobasidium* sp. and *Saccothecium rubi*.

Guerreiro and his team [76] concluded that the color and flavor of fresh Arbutus fruits stored at 0 °C do not change significantly for at least 15 days, which is a crucial feature for their fresh marketing. This makes it possible to counteract the rapid deterioration of the fruit at an advanced stage of ripening, thus contributing to interest in the fruit of this species.

In another study, edible coatings produced with alginate and supplemented with honey and essential oils were used to extend the shelf life of fresh fruit stored at 0, 3, and 6 °C. The best storage temperature to preserve the general nutritional quality was 0 °C and the fruits exhibited a good organoleptic quality as evaluated by a sensory analysis. The fruits showed a climacteric pattern between 3 and 7 days of storage, and the use of edible coatings increased the shelf life [77].

The fruit can be consumed fresh or traditionally processed into jams and jellies. Other uses have been explored for strawberry tree fruit, namely its incorporation into yogurts, confectioneries, breakfast cereals, and chutneys [66,78], in the form of pulp; fresh, dried, or dehydrated fruit; or crushed fruit without sclereids for chutney production.

Vacuum-drying has been used to evaluate the changes in some of its nutritional characteristics, antioxidant properties, and color. Orak and coauthors concluded that the fruit of the strawberry tree can be used in the food industry by drying due to the richness of the nutritional components, the antioxidant activity, and the attractive color of the fruit [79]. When drying was performed by hot air and the fruits were pretreated by dipping in ethyl oleate (EO) and by blanching using hot water at 80 °C (WB) for one minute, it was found that the EO pretreatment highly reduced the drying time, and pretreatment with WB proved to be effective for preserving the color properties of the fruit. Additionally, the color was improved if half the samples were dried compared to whole dried fruits [80]. When freeze-drying was used, dried strawberry tree fruits presented with better nutritional value, antioxidant activity, and sensory qualities [81]. Thus, drying strawberry tree fruit should make it an attractive and valued foodstuff for the food industry, due to the richness of its nutritional components, its antioxidant activity, and its color.

The use of strawberry tree fruit pulp, free from seeds and sclereids but with a similar chemical composition to the whole fruit, could be an excellent product for use in several food industries. The development of methodologies able to process strawberry tree fruits and extract the maximum amount of pulp is fundamental to increasing their potential use and the commercial value of this product in the modern food industry. Figueiredo and his team [82] studied carbohydrase-assisted extraction methodologies (Pectinex® Ultra SP-L and Viscozyme®) to produce pulp from strawberry tree fruits. Both were responsible for a significant increase in the pulp extraction yield. The treatment with Pectinex® allowed for higher pulp extraction yields to be achieved (54.9 ± 1.1%), with 27.3 ± 0.1°Brix being the highest soluble solids content obtained. Under similar test conditions, no significant differences were observed in the other physicochemical characteristics of the extracted pulp. The production of pulp using carbohydrase-assisted extraction provides encouraging results for increasing the range of value-added products, with significant applicability to the production of fruit drinks, jams, ice cream, etc.

4. Promising Applications of *Arbutus unedo* L. and Waste Valorization

4.1. Pharmacological Applications

Arbutus unedo L. possesses pharmacologically active compounds that have been traditionally used for medicinal purposes. Considering the high content of phytochemicals in strawberry tree fruits, mainly polyphenolic compounds, vitamins, and dietary fibers, it is to be expected that this fruit, with great nutritional and medicinal value, has been used since ancient times until today. They are mostly applied in the Mediterranean region for traditional, industrial, chemical, and pharmaceutical purposes [28]. The fruits are usually employed as diuretics and laxatives, antiseptics, digestives, carminatives, odontalgics, and cardiotonics [83,84]. Several studies have indicated that strawberry tree fruits have great pharmacological potential due to their antibacterial, anti-inflammatory, antitumor, and antioxidant properties [85–89]. With regard to the fruit, an ethanolic fraction rich in phenolic compounds exhibited potent antimicrobial activity against *Staphylococcus aureus*, *Bacillus subtilis*, and *Pseudomonas aeruginosa* [87]. Subsequently, an aqueous extract of the same fruit was incorporated into limpet pâtés, and demonstrated its ability to maintain microbial stability over a 90-day preservation period. The supplemented pâtés exhibited reduced microbial growth compared to their unsupplemented counterparts, with no pathogenic species detected [24,90].

Cancer remains a formidable global challenge as the second-leading cause of death, characterized by significant morbidity. This pervasive concern has spurred extensive research efforts to explore and validate innovative alternatives based on natural and edible products. These efforts have aimed to overcome the limitations associated with conventional anticancer drugs, such as their adverse side effects and limited specificity. Among the many plant species being studied, the strawberry tree has emerged as a promising candidate. While research on identifying the antitumoral compounds in strawberry trees' fruits is relatively limited, one notable study by Guimarães and his team [91] stands out. Their work demonstrated the efficacy of a methanolic extract from the strawberry tree for inhibiting the growth of several tumoral cell lines. Particularly noteworthy was its activity against NCI-H460 cells, which are associated with non-small lung cancer, highlighting the potent antitumoral properties of the strawberry fruit extract [24]. It was shown that *Arbutus unedo* strongly down-regulates STAT3 activation induced by carrageenan in the lungs, with a concomitant attenuation of all the parameters examined associated with inflammation, suggesting that STAT3 should be a new molecular target for anti-inflammatory treatment. A study conducted by Mariotto and colleagues demonstrated that acute lung inflammation is significantly attenuated by treatment with Arbutus [19]. But not only its fruits could be used in pharmacology. The leaves of *Arbutus* contain different compounds, and arbutin, as the most abundant bioactive compound in the leaves, is responsible for their antimicrobial activity. Its leaf extracts have exhibited the most potent antimicrobial activity against uropathogenic strains of *Enterococcus faecalis*. This enhanced activity may be attributed to the presence of bacterial β-glucosidase in *E. faecalis*, which effectively converts arbutin to hydroquinone. Arbutin is absorbed from the gastrointestinal tract, initiating a process wherein it is enzymatically hydrolyzed into aglycone hydroquinone and glucose by the intestinal microbiome, primarily under the influence of the enzyme β-glucosidase. The antimicrobial potency of arbutin is intricately linked to the activity of β-glucosidase [92]. The antimicrobial efficacy of Arbutus leaf extracts extends beyond arbutin, encompassing phenolic acids, such as cinnamic, ferulic, and caffeic acids, along with their esters. These compounds have demonstrated inhibitory effects on both bacteria and fungi. Their mechanism of action involves inducing irreversible changes in bacterial cell membranes, altering their cellular charge, intracellular and extracellular permeability, and physical and chemical properties [93,94].

The roots of the strawberry tree also have promising potential. Research conducted by Djabou and his team [95] revealed that the ethyl acetate extract obtained from Algerian *Arbutus unedo* L. roots contains high concentrations of phenolic acids. Remarkably, this extract exhibits radical scavenging properties that are 2–3 times higher than those of the reference antioxidant, ascorbic acid. Moreover, it demonstrates exceptional antibacterial activity against both Gram-positive and Gram-negative bacteria, with minimum inhibitory doses as low as 25 µg/disc. Strawberry trees' roots have been subjected to extraction processes to obtain phenolic-rich products with antimicrobial potential.

Traditional extraction methods have shown limited effectiveness against *S. aureus* and *P. aeruginosa* with methanolic and aqueous extracts, although the aqueous extract has showed moderate efficacy against *E. coli* [85]. However, employing advanced techniques, such as Pressurized Liquid Extraction (PLE), markedly enhances the antibacterial properties. This is exemplified by the methanolic PLE product, which showed increased activity against *S. aureus*, *E. coli*, and *Salmonella* spp. [85,96].

4.2. Cosmetics Applications

The cosmetics industry has shown increasing interest in natural ingredients, and *Arbutus* offers a range of beneficial properties for skincare and haircare products [26,65,97].

The cosmetics applications of Arbutus extracts include their antioxidant, moisturizing, and anti-aging effects. This section discusses the potential use of Arbutus extracts in the formulations for skincare products, hair treatments, and sunscreens. Arbutus stands out for its remarkable antioxidant properties, boasting potent antiradical and reducing power alongside robust total antioxidant activity. Additionally, it exhibits promising potential as a skin-whitening agent, demonstrating high anti-tyrosinase activity. Notably, it showcases no cytotoxic effects and displays moderate anti-inflammatory activity. Leveraging its high yield efficiency and multifaceted benefits, water reflux has been chosen as the method for formulating a cosmeceutical oil-in-water nanoemulsion. This nanoemulsion not only maintains an optimal pH but also stability, making it an ideal vehicle for harnessing the therapeutic potential of *Arbutus unedo* in skincare applications [21]. The plant's secondary metabolites have the capability to regulate the activity of enzymes implicated in skin aging. One such enzyme, often targeted by the cosmetics industry, is tyrosinase. This copper-containing enzyme plays a pivotal role in catalyzing melanin biosynthesis in human skin. While melanin offers protection against environmental factors, particularly UV radiation, its excessive production can result in hyperpigmentation, leading to skin issues, such as age spots, melasma, and post-inflammatory hyperpigmentation, thereby contributing to a flawed and prematurely aged appearance. Hence, targeting tyrosinase activity presents a viable approach for addressing pigmentation disorders and formulating effective cosmetics products. *Arbutus unedo* leaf extracts have been analyzed for their ability to inhibit tyrosinase activity. Tyrosinase, a copper enzyme, plays a pivotal role in the initial stages of melanogenesis. It catalyzes the conversion of L-tyrosine into L-DOPA through hydroxylation, and subsequently oxidizes L-DOPA into o-dopaquinone, a compound that spontaneously polymerizes to form melanin—the primary determinant of skin color. The overproduction of melanin can result in hyperpigmentation disorders, such as lentigo, melasma, and general hyperpigmentation. Consequently, tyrosinase inhibitors hold promise as potential skin-whitening agents. While hydroquinone is a well-known tyrosinase inhibitor, its adverse effects have raised significant concerns, prompting the exploration of natural compounds with tyrosinase-inhibitory properties. The evaluation of Arbutus extracts has focused on inhibiting both catalytic functions of tyrosinase: monophenolase (inhibition of L-tyrosine hydroxylation to L-DOPA) and diphenolase (inhibition of L-DOPA oxidation to dopaquinone) activities [21,98,99].

4.3. Waste Valorization as Natural Dyes for Textiles

Arbutus unedo L. leaves and fruits contain pigments that can be extracted and utilized as natural (bio-)dyes. As mentioned before, "*aguardente de medronho*" is a typical fruit spirit drink very appreciated in Portugal, and, more recently, several other applications of the fruits, such as the production of jams and ice creams, have become common. The macerated/crushed pulp of the fresh fruits not used in food production and the solid residue after the distillation of fermented fruits generate a large volume of waste. A possible valorization of this waste is its use as a bio-dye source for the textile industry [100]. The replacement of chemical dyes in the textile industry with natural dyes derived from bioproducts/residues is a relevant topic that could promote environmentally sustainable processes and a circular economy. This possible way of valorizing the distillation mash waste resulting from "*aguardente de medronho*" production could also provide an extra economic income for local populations.

Coelho Pinheiro and her team [100] directly used mash waste, after filtration, in dyeing assays carried out at 50 °C with agitation (320 rpm) for 100 min. Three different textile substrates were used: cotton, wool, and cationized cotton. The dyeing assays were performed in duplicate, and a control sample immersed in water and subjected to similar conditions was also used for the dyeing effectiveness evaluation. As the color fastness performance of dyed samples is a crucial parameter for evaluation in the textile industry, the samples were washed with cold water (20 °C) and hot water (45 °C) after being dyed. Finally, they were dried under natural-light exposure (half of the sample surface was protected from light exposure using a black card) for one week. The color assessment of the dried dyed samples was conducted according to the CIE (*Commission Internationale de l'Eclairage*) system, measuring the $L^*a^*b^*$ coordinates using a colorimeter. By a comparison of the $L^*a^*b^*$ coordinates of the dyed samples and of the control, the ΔE^* parameter was obtained, quantifying the magnitude of color difference. Values of $\Delta E^* > 5$ indicate that any observer will see two different colors [101]. A palette of uniform earth tones was obtained, ranging from an intense brownish gray (mean $\Delta E^* = 25.37$) to a light cream (mean $\Delta E^* = 7.64$), with the cationized cotton substrate presenting the more intense color.

The proposed eco-valorization of the waste obtained from arbutus unedo fruit manufacturing requires further exploratory studies to consolidate improvements in its color fastness properties, but the hues and tones obtained in the fabrics made with the waste have shown potential for commercial acceptance. There are many advantages to using natural dyes, such as sustainability, biodegradability, and the potential for creating additional profit from waste without commercial value.

5. Future Directions

The multifaceted roles of strawberry tree (*Arbutus unedo* L.) forests in Portugal have been increasingly recognized, but several promising avenues remain unexplored. Future research should not only deepen our understanding of the ecological and socio-economic functions of this species, but also translate that knowledge into practical applications supporting sustainable development. The key directions for future research include the following:

- An assessment of fertilization based on the productive potential of the site (climate, parent rock, soil, and exposure), orchard development stage, soil organic matter content, soil and leaf nutrients, and fruit production;
- The establishment of progeny trials of the 50 parents (50 clones) installed in the first-generation seed orchard;
- The improvement of the knowledge of symbiotic associations to increase survival after planting, tolerance to water stress, and, where possible, stimulate the production of edible mushrooms;
- Assisted plant selection with molecular markers, linked to fruit quality or tolerance to water stress, according to the main objectives and constraints;
- An assessment of the genetic diversity of Arbutus unedo L. for breeding programs and conservation efforts in Mediterranean regions;
- The development of new functional products using strawberry tree fruit's bioactive compounds and nutritional value;
- The improvement of fermentation and distillation processes to optimize the production of distilled beverages with lower methanol levels;
- The exploration of novel preservation techniques, including natural edible coatings, to extend the shelf life of strawberry tree fruit;
- The optimization of pulp extraction methods for increased yield and applicability in food industries like fruit drinks and novel gastronomic products;
- The identification of new applications in pharmacology and cosmetics, contributing to the development of natural therapeutics and green consumer products;
- The exploration of novel applications for fruit-processing residues, integrating waste management with circular economy principles, could provide models for sustainable product innovation.

By addressing these research gaps, future studies could not only enhance the scientific understanding of strawberry tree forests, but also foster innovative practices that could integrate ecological resilience with socio-economic development. This integrated approach will be essential for ensuring the long-term sustainability and multifunctionality of these unique forest ecosystems in Portugal.

6. Conclusions

The multifunctionality of strawberry tree plants and fruits provides local benefits in four main dimensions: environmental, economic, social, and industrial.

Strawberry tree plants play a crucial ecological role in the resilience of the forest ecosystems in Portugal, combating desertification, forest fires, and climate change, and influencing plant production. Additionally, it enhances agroforestry areas by mitigating erosion and increasing soil organic matter. The use of the strawberry tree in food and beverage production, such as jams, jellies, and spirits, among others, not only benefits the agrifood sector but also has positive social and economic impacts on the local populations.

The plants and fruits can be used as the sources of several bioactive compounds with pharmaceutical and cosmetics applications. Furthermore, the valorization of strawberry tree spirits' mash waste, through its application as bio-dyes for textiles, is considered a promising research area. Thus, the strawberry tree stands out not only as a valuable environmental resource but also as a crucial element for sustainable local development.

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