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Biodegradable Raffia as a Sustainable and Cost-Effective Alternative to Improve the Management of Agricultural Waste Biomass

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Abstract: The transition from intensive conventional agriculture to sustainable agriculture has become a global priority. This is due to the need for environmentally friendly agriculture to ensure sufficient food for a rapidly growing population. The bioeconomy is essential to progress in the field of sustainable agriculture. It contributes to the conservation of biological resources through circular and comprehensive management. The bioeconomy prioritizes the reduction and reuse of materials and products. The focus of this study is the use of biodegradable/compostable raffia in protected horticultural crops in the Province of Almería (Spain). The analysis and evaluations, based on an extensive literature review and information given by stakeholders, determined that biodegradable raffia use significantly improves the management of residual biomass in Almería. However, biodegradable raffia is only used in a small percentage of crops even though it is a sustainable alternative and profitable for farmers. The economic analysis incorporates the higher cost of recycling non-biodegradable raffia.

Keywords: sustainable agriculture; horticulture; agricultural waste biomass; biodegradable raffia; trellis; alternatives to raffia; greenhouse crops; circular economy; bioeconomy

1. Introduction

1.1. Transition from the Conventional Intensive Agricultural Production Model to a Circular and Sustainable One

Agriculture is responsible for a quarter of the greenhouse gas (GHG) emissions that contribute to climate change [1,2]. A high percentage of these emissions, including methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), are produced by the intensive use of nitrogen fertilizers, the decomposition of agricultural residues, and the burning of large amounts of crop residue [3,4]. The forecast is for continued increase of these emissions in the future [1]. Today, these emissions are responsible for the higher frequency of extreme weather events, such as torrential rain and prolonged drought [5]. These climatic conditions accelerate soil degradation and negatively affect agricultural productivity, putting food security at risk [6,7]. By 2030, it is estimated that more than 122 million people linked to agriculture could be living in extreme poverty as a result of the consequences of climate change. Likewise, by 2050, this phenomenon could lead to an increase in the prices of basic food items, such as cereal. This situation highlights the urgency of transforming the current food system into a more sustainable one. By 2050, it will be necessary to increase food production by 49-percent [8], while reducing GHG emissions and increasing the capacity to adapt to climate change. This is one of the main goals of the Sustainable Development Goals (SDA) of Agenda 2030: "To end hunger, achieve food security and better nutrition, and to promote sustainable agriculture" (target 2.4) [9,10]. The main challenge of sustainable agriculture is to prioritize the connection between the economic, social, and environmental dimensions of sustainability. The goal for 2030 is for profound changes in the agri-food system [2,11], contributing to the achievement of the climate objectives of the Paris Agreement [12].

Systemic change is required for policies and strategies to incorporate the ideas of circular economy and bioeconomy while providing the appropriate tools for the transition from linear to circular and sustainable agriculture [8,13]. An agricultural model whose main pillars are sustainability and circularity promotes the sustainable production, use, and conservation of biological resources [12,14–16]. It enables increased food production with fewer consumables and lower polluting emissions [13,17]. The existing intensive agricultural system generates large quantities of crop residue, which many farmers cannot manage properly. Under circular bioeconomy, this waste becomes a valuable, sustainable resource with multiple uses [18–21]. New processing technology for recycled waste produces high-value products with novel properties and uses [22,23]. Increasing the circularity of agricultural residue contributes to the reduction of GHG linked to the use of non-renewable materials [17,24], and also increases the accumulation of carbon in the soil (carbon sequestration/retention) [25,26].

1.2. Protected Horticulture and Its Role in Food Security and the Fight against Climate Change

The important fruit and vegetable sector, which provides essential products for a healthy diet [27], is highly vulnerable to anthropogenic climate change [1].The negative effects of the climate variability on fruit and vegetable production are diverse and include changes in vegetative and reproductive processes, decreases in crop production and product quality, and a higher incidence of pests and diseases [28]. In many cases, the response has been to modify crop varieties and production systems [29–32]. Protected crops, which are mainly located in the Far East and the Mediterranean basin, have grown significantly and continuously in the last several decades [10]. In the EU, the cultivated area was approximately 175,000 ha in 2015 and the rate of increase was close to 4.5-percent between 2005 and 2013 [33]. The increase results from the need to protect crops, mainly vegetables, from adverse weather conditions throughout the year [34,35]. Greenhouse cultivation is particularly suitable for controlling climate parameters and indoor environmental conditions, conserving resources, and counteracting the effects of climate change, thereby enhancing global food security [33,36,37].

The contributions of the horticultural production system, which is considered the most intensive in the world [38], have been significant. However, it is important to note that the construction of greenhouses requires a large number of synthetic materials, such as polyethylene (PE) and polypropylene (PP) [39,40], which are used for roofing, mulching, seedling pots, ropes and clips to hold plants, among others [41,42]. This has led to the production of large amounts of non- biodegradable plastic residue [43,44]. Thus, one of the main problems with intensive horticulture is the generation of almost a million tons of polymeric material per year [41]. Recycling is irregular with negative environmental impact [41,42]. Some of the polymeric material is thrown into landfills [33]. The environmental impact is also linked to the production process of synthetic polymers that are manufactured from fossil raw materials [43,45].

1.3. The Importance of Protected Horticulture in the Economic and Social Development of the Regions and the Challenges of Moving towards a More Circular and Sustainable Model

During the last 20 years, Mediterranean and southeast European countries have specialized in the production of leafy vegetables in a protected environment. They have achieved this task very competitively, mainly with small producers using family labor [35,37]. This production model has contributed importantly to the national economies in the Mediterranean region [35,38], especially in the Spanish province of Almería, which has the largest area covered by greenhouses in the world [10,46].These greenhouses support the intensive production of fruits and vegetables [10,47]. Almería's contribution has made Spain the leading exporter of fruit and vegetables in the EU and the third largest in the world after China and the USA [48].

Intensive protected horticulture has been the most dynamic sector in this region's agriculture. In the last 50 years, its contribution to socioeconomic transformation and growth has been huge [49,50]. This sector has directly contributed more than 25-percent of the GDP of Almería while making possible the important development of auxiliary industry [51,52], that has increased its employment sources, significantly improving the standard of living of farmers and the surrounding population [53]. Since 2000, the province of Almería has increased its winter crop area by 16-percent, from 26.531 ha to 31.614 ha, and its effective area of cultivation by 14-percent, from 39.094 ha to 45.680 ha. In this progression, the effective crop area is larger due to the strategy of production in two crop cycles per year [10]. Greenhouse structures and crop production techniques have evolved steadily [39], allowing farmers to achieve high productivity. An environmental problem results from the higher generation of residual biomass at certain times of the year [54]; the accumulation is difficult to manage properly [55–59]. Protected horticulture in Almería produces an estimated 1,370,743 t/year of residual agricultural biomass, of which only a small percentage is used on the farms [10].

The main horticultural crops in southeast Spain, such as tomatoes, peppers, eggplants, cucumbers, beans, and zucchini are trellised to keep the plant straight [60,61] and to improve the quality of the fruits and the production of the crops [62]. This fastening technique generally utilizes non-biodegradable polypropylene threads (raffia) [62–64], which in most cases are mixed with plant debris at the end of the crop cycle [57,65]. Self-management of crop residue (production of compost and/or green fertilizer) is a profitable practice for farmers, allowing the reduction of costs and the improvement of soil conditions, while increasing circularity and sustainability in greenhouses [10,35,37,66,67]. However, it is seldom implemented due to the difficulty of treating biomass waste mixed with plastic raffia residue [68]. The separation of this raffia for on-site waste management [69], represents an important additional cost for the farmer and it is a difficult task to carry out. Sustainable management practices and valorisation of agricultural residual biomass have been widely evaluated and defined as elementary to achieve the objectives of the circular bioeconomy [10,44,57,70–72]. Many of these practices provide additional benefits to farmers, who in turn could contribute to the conservation of their environment in a more responsible manner [73]. Farmers often suggest certain measures, such as the use of biodegradable/compostable raffia, involve additional costs. Many of these farmers say these expenses hurt their bottom line.

This study presents the following question: Is biodegradable/compostable raffia a sustainable and profitable alternative for protected horticulture in the province of Almería? From a microeconomic point of view, the aim is to analyse whether the use of this type of raffia is a profitable option for farmers and whether or not this practice contributes to the sustainability of horticulture in south-eastern Spain. Considering the importance of crop management in the province of Almería, action needs to be taken towards a more sustainable and circular horticulture [59,74–76]. This study shows the results of the economic evaluation and the environmental/social benefits that could be obtained by the replacement of plastic raffia with biodegradable and/or compostable raffia, which contribute to the reduction, use, and improved management of agricultural residual biomass [33,36].

1.4. Background, Current State of the Research Field and Theoretical References

Significant research has focused on the use of various materials and inputs of biological and/or biodegradable origin in modern agriculture and horticulture. According to this scientific research, one of the most studied topics since 1993 has been the replacement of polyethylene plastic covers, films and/or mulches with others of biodegradable materials. These materials are derived from biopolymers, carbon ashes, corn and wheat starch, and agricultural waste [41–43,45,77–79]. Many of these studies are based on previous tests and they show relevant data on the characteristics, properties, advantages, and limitations on the use of biodegradable plastic in agriculture.

Some of these studies indicate that at least 30-percent of plastic waste produced by agriculture comes from the use of short-term (two years or less) materials, such as clips, wires, nets, and geotextiles [80,81]. The research also highlights the potential of the use of these biodegradable materials in organic and sustainable production systems. The studies emphasize the reduction of plastic waste and the possibility of using them as one of the main advantages in the use of biodegradable materials in agricultural applications [82,83]. The reduction of harmful environmental impacts and the increased sustainability of production are highlighted by this research [41–43,45,84–87]. Although these studies mention the multiple benefits of using biodegradable materials in agriculture, there are also challenges and restrictions in its implementation due to the need to improve the quality of these products and its high cost compared to conventional materials [86,88–90].

More than 20 studies on greenhouse crops and agricultural waste management in the province of Almería [10,40,62,71,91–96] were reviewed. Some of these documents include technical reports from public and private organizations that claim the mixture of vegetable waste from greenhouses and non-biodegradable waste complicates its processing and affects the cost of reusing the waste biomass as a new subproduct [33,57,68,69,75,97–103]. Several of these studies suggest the use of biodegradable raffia is a solution to this problem.

Table 1 lists research projects conducted to evaluate the viability of raffia and other fixing elements made from biodegradable materials for crop support. These studies have focused mainly on the evaluation of the mechanical properties of these materials, along with their ability to degrade and transform into compost.

All of these studies show that the use of biodegradable and compostable materials, such as raffia and paper clips, contribute to the environmental sustainability of horticultural systems. They also highlight that this practice expands the possibilities for organic matter production, which can be used on farms. One of these investigations conducted a comparative cost analysis and found that the use of biodegradable raffia involves higher costs compared to polypropylene raffia [63]. Another topic mentioned is the economic advantage of farmers using biodegradable clips, due to the lower cost of processing vegetable waste. This is also advantageous for recovery plants, which could reduce processing time and improve the quality of the compost [81]. Although most of these studies have been developed in the province of Almería, none of them offer a complete analysis of the subject or illustrate an economic evaluation that incorporates specific variables considered in the present study.

The research examined represents significant contributions and confirms the importance of the study. The data collected are based on numerous international and local policies, regulations, and strategies that promote the use of biodegradable and compostable materials in agriculture [12,59,63,76,104].

Table 1. Research related to the use of raffia and other biodegradable fixing elements for crop support.

Year	Name of the Study	Type of Alternative Materials Analyzed	Type of Parameters Analyzed/Features	Key Findings of the Study	Conclusions	BIBLIOGRAPHICAL REFERENCE
2008	Use of biodegradable raffia for tomato crop trellising in long cycle under greenhouse	Jute-Rattan-Potato and corn starch	Maximum force Maximum elasticity Gradient	Raffia made from potato and corn starch + rattan, has less resistance to breakage and less gradient. Jute is more elastic.	Different alternative biodegradable materials can be found on the market, which makes it possible to obtain a completely organic waste.	[62]
2009	Degradation of greenhouse twines derived from natural fibres and biodegradable polymer during composting	Yarn of cotton, jute and a biodegradable polymer yarn (EcoPLA)	Test of biodegradation (Composting) for 15 weeks. Monitoring of the physical properties of the yarns: linear density, % weight loss and resistance to traction.	Composting tests showed that all three materials could be easily degraded in a composting environment within a reasonable time.	EcoPLA yarn has the advantage of being the most environmentally compatible biodegradable material.	[105]
2016	Management of vegetable waste with raffia	Cellulose biopolymer (20 kg) Cellulose biopolymer (45 kg) Jute-Rayon P Sisal Biopolymer	Tensile test-Deformation of new and used raffia	The results of the composting test show that after 11 months all materials degrade, even without being shredded, except the Biopolymer.	A high number of material breaks. There is a large availability of materials that meet strength and degradation specifications.	[102]
2016	Action lines for the management of plant residues in Andalusian horticulture. Annex II. Cost analysis of the use of biodegradable raffia vs. propylene raffia.	Cellulose raffia/biopolymer 100% biodegradable	Economic	The results obtained show that the increase in cost of using biodegradable raffia is 419.29 euros/ha more than conventional raffia.	The number of companies that market or distribute biodegradable raffia is low. Three companies have been identified in the province of Almería.	[63]
2017	Biodegradable Materials in Agriculture: Case Histories and Perspectives. Case History: The Greenhouse Plastic Materials in Greenhouses	Clips of biodegradable and compostable materials	Basic test of functional properties: resistance of the thread under stress. Laboratory and field composting tests.	The clips were very well decomposed in 4 months and the compost obtained could be certified and commercialised.	The use of compostable clips provides advantages in reducing pollution of the compost and represents less costs for farmers and composting companies.	[81]
2019	Different applications of biodegradable and compostable materials in agriculture	PLA Polylactic Acid threads	It is a material highly resistant to ultraviolet radiation. It is strong, lightweight and has a low moisture absorption.	PLA threads can be recycled as green waste and composted at the same time with other compostable materials	This alternative is already on the market (Netherlands) and can replace non-biodegradable materials. It contributes to savings for farmers by reducing waste disposal fees.	[80]

Table 1. *Cont.*

Year	Name of the Study	Type of Alternative Materials Analyzed	Type of Parameters Analyzed/Features	Key Findings of the Study	Conclusions	BIBLIOGRAPHICAL REFERENCE
2019	Inorganic Waste Management in Greenhouse Agriculture in Almería (SE Spain): Towards a Circular System in Intensive Horticultural Production	Biodegradable yarn made from recycled cotton and agro-nutrients, jute fibre, and other natural materials, cellulose-rayon.	Compostable materials	The use of these materials prevents the work of separating the ropes from the rest of the organic elements once the crop has been harvested. This allows to reduce costs and to produce compost in the farms.	This practice is part of the list of Best Available Techniques (BAT) for the Management of Inorganic Greenhouse Waste in Almería.	[71]
2020	REINWASTE Project (MED Cooperation Programme 2014–2020. Institute for Agricultural and Fisheries Research and Training (IFAPA in Spanish)	Alternative 1: use of reusable raffia. Alternative 2: use of natural raffia of vegetable origin (jute), 100% compostable. Alternative 3: use of mixed biodegradable raffia (natural + polymer).	- Degree of handling. - Percentage of compostability - Percentage of breakage (tensile strength, elasticity) - Cost analysis	Not yet obtained	The project is currently in the pilot testing phase.	[103]

1.5. Characterization and Description of the Trellising Techniques in the Horticulture Crops in the Province of Almería

1.5.1. Importance of the Trellising Work in Horticulture Crops

Since ancient times, materials such as canes and sticks have been used to keep plants upright and optimize the developmental conditions of horticultural crops [52,64,106,107]. Certain herbaceous and shrubby species lack the rigid and resistant stems that would allow them to stand vertically on their own during fruiting [40,108,109]. At the beginning of the 1980s, the consolidation of the intensive horticulture model in the province of Almería, as well as the evolution of the design and improvement of greenhouse structures [110,111], required modern methods of trellising. New methods and materials were introduced, including non-biodegradable plastic raffia fibre [39,63,64,109,112]. The plant is tied with raffia fibre to guide wires or structural elements of the greenhouse at various heights and in a vertical and/or horizontal direction, depending on the trellising technique used [62,66,83]. This fastening and guiding system is essential for the majority of protected horticultural crops as it enables the following:

To improve the plant airing and to support the use of solar radiation.
To prevent the contact of fruits and leaves with the ground.
To reduce and control the incidence of plant illnesses.
To improve the efficacy of phytosanitary products.
To ease the processes of pruning, stem removal, fruit harvesting, and any crop maintenance work on the farms.
To enlarge the density of the plantation in order to increase the productivity of the fields.
To improve the quality of the fruits (greater homogeneity in visual aspects).

1.5.2. Crop Trellising Techniques in the Province of Almería and Characterization of the Main Elements Used

There are different systems utilized for trellising. Choosing the right one will depend on the design of the greenhouse, the needs and morphology of the crops, and the economic resources available for the implementation of each technique. The choice of the optimal technique leads to greater production and quality of the fruits [112]. Some of the main techniques used in trellising horticultural crops in the Province of Almería are featured in the photos below in Figure 1.

Trellising systems are composed of a series of fastening elements that complement each other and are indispensable for their proper functioning [109]. The evolution of these techniques has led to greater use of material. The elements used to implement the trellising in south-eastern Spain are described below.

(1) Hangers (hooks)

Generally, these are metal (steel) and/or plastic hooks, which support the wire and allow the plant to be lifted as it grows. Some of them have a reel that rotates on a horizontal axis and allows the tutor wire to be unwound as the plant grows. The duration of these gadgets is two years and 18 to 20 m of raffia has to be placed in each hanger or reel.

(2) Clips

Different types of clips are used, both to hold the plant to the raffia and to keep the rachis of some fruit bunches in a specific position, as well as to keep the raffia used in the pepper bundles. Although previously made of metal, almost all the material used now is plastic.

(3) Thread (Raffia)

Synthetic thread often made of polypropylene (PP), polyethylene (PE), or thermoplastic polymers that are lightweight, flexible and consistent [39,43]. These threads allow different parts of the structure to be fastened to the plant to keep it in a vertical position during its development. For more than a decade, there have been biodegradable yarns on the market [113] that are made from different materials.

The way these fasteners are installed optimizes the benefits of trellising, but also facilitates the handling of raffia during the harvest. The installation method also reduces by 20-percent the cost of separation from other vegetable residues when the fasteners are not biodegradable [101,114].

Dutch pruning trellising in peppers

Hook-and-loop trellising system in tomatoes

Conventional or bundle trellising in pepper crops

Trellising in cucumber crops

Figure 1. Trellising systems in the horticultural crops in Almería.

2. Materials and Methods

2.1. General Description of the Process

This research was developed primarily in two stages. The first stage consisted of an extensive review and bibliographic analysis of studies, technical reports, strategies, projects, legislation, and other information on the management of agricultural residual biomass and the use of biodegradable raffia in horticultural crops at the international, national, and local levels. The consultation sources changed according to the type of document. The primary documents are the Scopus database, as well as public and private websites of local and international entities.

Figure 2 describes information obtained from various sources. The VOSviewer software (version 1.6.11.0) was used to evaluate the scientific literature obtained from the Scopus database. This is a particularly useful tool for the visualization of the most relevant aspects of these investigations.

The information collected in the first phase offered a general contextualization of the topic. Stakeholders, data gaps and questions not sufficiently clear were identified. In the second phase, the stakeholders who could provide relevant information due to their connection with the research subject were defined. These included local public entities with competence in agricultural waste regulation, agricultural research centres, companies producing and/or marketing biodegradable materials and waste recovery. Questionnaires with semi-structured questions and specific requirements for each entity were developed.

Research institutions were asked to provide information about projects that were being developed in this area. Updated information on prices, the amount of waste treated, and the amount raffia processed was requested. Waste recovery companies in the province of Almería were consulted on waste management, current problems, and improvement actions.

In addition, information was requested from companies selling biodegradable materials in the province of Almería. The companies were asked, specifically, to provide information on the type of biodegradable raffia sold, the market behaviour, and the trend of consumption witnessed in recent years. The first means of communication with these entities was by e-mail. In cases where there was no response, telephone consultations were made. Interviews with quality and environmental managers of public and private companies were also organized.

2.2. Key Process Steps

Figure 2 lists the main stages that were carried out for the preparation of this study.

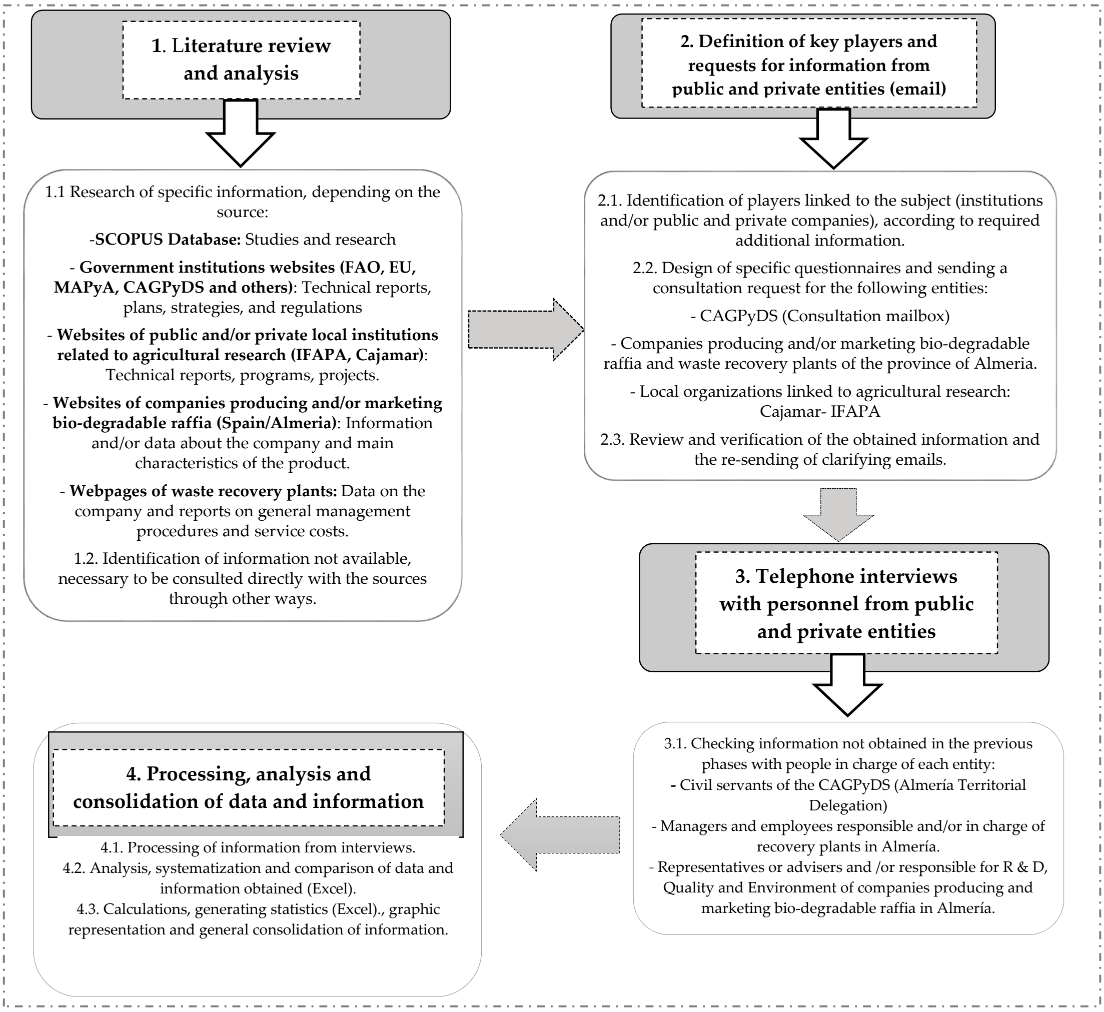

Figure 2. Main stages of the study elaboration process. FAO: Food and Agriculture Organization of the United Nations. EU: European Union. MAPyA: Ministry of Agriculture, Fisheries and Food. CAGPyDS: Department of Agriculture, Livestock, Fisheries and Sustainable Development of the Regional Government of Andalusia (Junta de Andalucía). IFAPA: Andalusian Institute for Research and Training in Agriculture, Fisheries, Food and Organic Production.

3. Results and Discussion

3.1. Main Crops in the Province of Almería that Are Grown Using Trellising Techniques and Estimation of the Amount of Raffia Used According to Type of Crop

In the protected horticulture of the province of Almería there are eight crops. Specifically, three of them are solanaceous plants: tomato, pepper, and eggplant; four curcubits: cucumber, zucchini, melon, and watermelon; and one legume: green beans. The fruits of all of these crops are sold in the market. The area cultivated in the 2018–19 season was 45,668 ha [47]. Tomatoes, peppers, zucchini, and watermelons were the crops with the highest production and the largest area cultivated in the last 15 years [10]. Tomato cultivation can be done in two short cultivation cycles of 150–170 days or in one 300–330 day cycle. This crop has been the most representative of the region, although during the last several seasons it has had a stable area of around 10,000 to 10,500 hectares and in the 2018–19 season it had an 8-percent decrease in production compared to the previous season. Green beans are the crop with the biggest loss of cultivated surface and production during the last several years [47,115]. It is important to highlight that the area of protected horticulture under organic production protocols in the province of Almería has increased in recent years from 891.64 ha in 2010 to 3211.82 ha in 2019, which represents an increase in area of more than 350-percent [59,116].

The vegetable species of these eight crops have a different morphology. The shape that is given to the plant through shape pruning and the use of trellis differs depending on the species and the distinctive features of different crops and they have a physiologic impact on important factors as agronomic productivity and the quality of the harvest. Due to agronomic factors included in the productivity of the farms, only six of the eight mentioned crops are still trellised because melon crops, to which this cultural technique was also applied, are no longer trellised. Based on this fact, the approximate amount of raffia that is used in greenhouse crops in the province of Almería was calculated (Table 2).

Table 2. Main trellised crops in the province of Almería and estimation of the amount of raffia used by type of crop.

Crop	Area(ha) 2019	Type of Technique		Average of Raffia Used			Observations
		(ST)	(HTb)	(kg/ha)	Total (kg/Year)	Total (t/Year)	
Tomato	1715	×		160	274,400	274	LCC and hook
Tomato	7840	×		53	415,520	416	SCC
Pepper	9865	×		80	789,200	789	
Pepper	695		×	132	86,988	87	
Cucumber	5023	×		53	266,219	266	
Zucchini	7349	×		33	242,517	243	Trellising 10%
Eggplant	2164	×		80	173,120	173	
Green beans	243	×		40	9720	8	
		Total			2,257,684	2256	

Source: Prepared by the authors from de [47,51,61,63,64,95,117–119]. SCC: Short Cultivation Cycle. LCC: Long Cultivation Cycle. ST: Sprout Trellising. HTb: Horizontal Trellising (bundle).

On average, approximately 2256 tons of raffia were used during the 2018–19 season. Approximately the same amount was used during the 1999–2000 season. In the earlier era, the cucumber crop required the highest amount of raffia, 1684 t or 40-percent of the total [52]. As shown in Table 2, today the pepper crop requires the greatest amount of raffia during trellising, approximately 39-percent of the total, while cucumber only requires 12-percent. The data obtained for the 2019 season are in line with data obtained for other seasons: on average 70–80 kg of raffia are used in Almería for each hectare of greenhouse area [67].

3.2. Characterization of the Use of Non-Biodegradable Raffia in Greenhouses and Main Problems Associated with Its Use

Polypropylene (PP) raffia has a longer life span than other materials. It is flexible, has high tensile strength, and is adaptable to different trellising techniques [95].These properties protect against breaking and mechanical damage to plants [40,62,120]. The low cost of this material [44,90] makes it preferred by farmers for its use in Almería's horticultural crops. The majority of the plastic materials used for the trellising are made of polymers and "oxodegradable" additives. These additives are regularly used to improve the properties of the plastic or reduce its cost; they allow plastic fragmentation due to heat or UV radiation. However, such plastics are not biodegradable or compostable [44,121]. This is a major problem for its management since it limits the option of recycling [40] and leads to environmental contamination by microplastics [122].

Plastic materials deteriorate due to environmental factors including wind, humidity, temperature, and rain. These factors, along with age, change the physical, chemical, and mechanical properties of the materials, even in greenhouse environments [43,44,113]. Such materials can only be used for 2 to 4 years before replacement [71,101]. Raffia and other plastic elements used for trellising in protected horticultural crops in Almería are usually used only once per crop cycle (6 or 12 months) [40].

Self-management activities of vegetable residue (green fertilizer, compost production, biochar, among others) in Almería greenhouses are scarce and are basically carried out in farms with a focus on organic production [10]. This is why the quality of the plant residue generated is not a topic of interest to farmers engaged in conventional horticultural production. For this reason, raffia gets mixed with waste biomass during removal at farms [40], which produces a mixed waste of organic materials contaminated with inorganic materials [50,57,63,96,123].

Plastic materials manufactured from polypropylene (PP) have been broadly studied and their negative impacts on the environment and human health have been clearly identified [41–44,113,124,125]. The negative impacts result from the manufacturing process [121,126], during the use and management stages in the greenhouses, and in the final disposal phase of this material in Almería. Negative externalities affect socio-economic and environmental conditions (Figure 3).

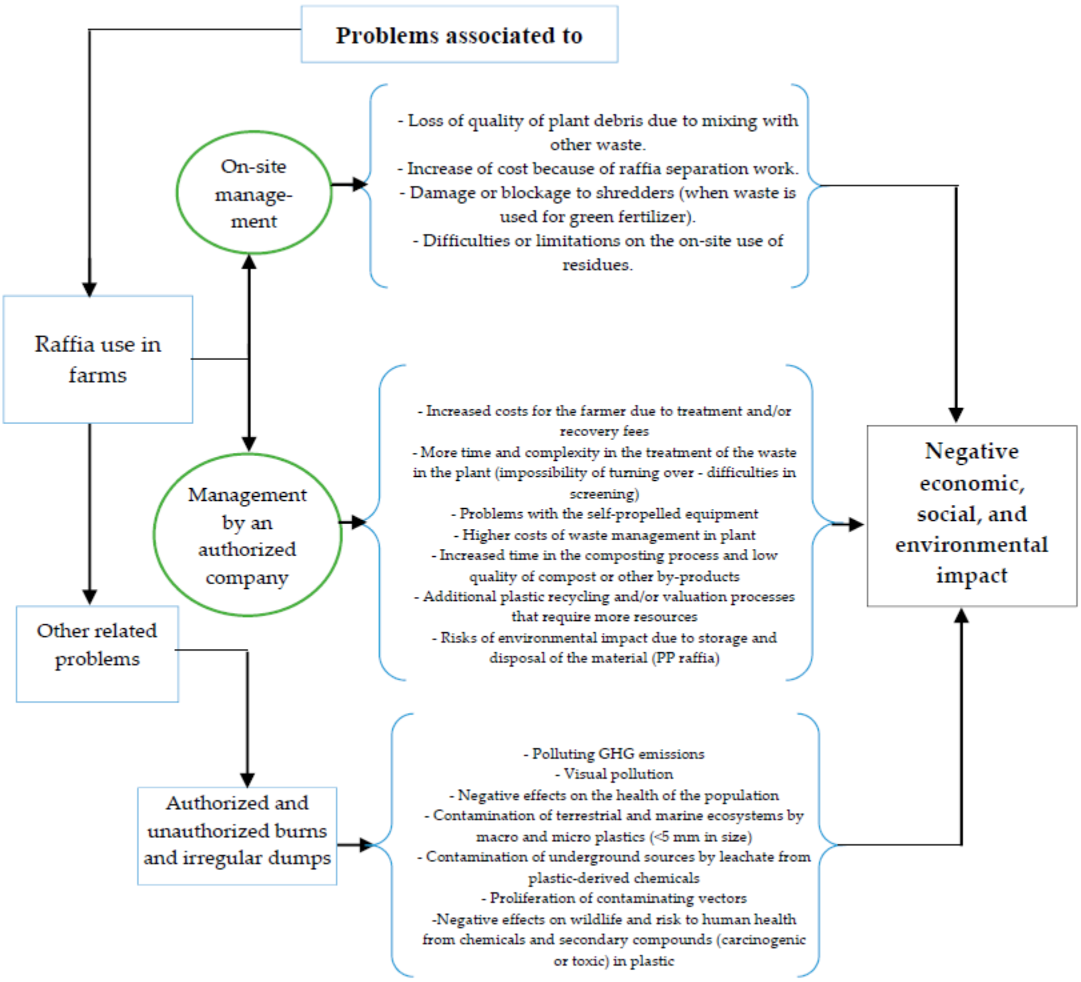

Figure 3. Main problems related to the use of non-biodegradable raffia. Source: Prepared by the authors from [33,41–44,63,71,76,96,100,101,121,122,124,125].

3.3. Estimation of the Residual Non-Biodegradable Raffia Generated in Almería Horticultural Greenhouses

The absence of detailed records on the amount and characteristics of vegetable residue generated annually on agricultural farms [10,57] makes it difficult to know exactly how much residual raffia is produced. To calculate the approximate amount of residual raffia generated yearly, we took into consideration the total amount of raffia used per year, which is 2,580 t. This amount includes the 405 t of biodegradable raffia, generally three-layer jute used in the 3000 ha and produced under the integrated production protocol. The conclusion is that the Protected Horticulture of Almería consumes 2175 t of plastic, non-biodegradable raffia per year, or 84-percent of the total raffia used. Residual raffia is generated almost equally in the final months of each cycle (mid- December/mid- February and mid-May/mid-June). During these months a massive harvest of crops takes place, and the total removal of raffia is close to 80-percent of the annual total used [10,40,123].

3.4. Current Management of Non-Biodegradable Raffia Used in Almería Horticultural Greenhouses

Ninety-one-percent of the greenhouse area in the province of Almería is condensed in western (Poniente) Almería, with 21.545 ha. Campo de Níjar and Bajo Andarax have 8.748 ha [10], which makes these the areas with the highest production of crop residues. For the most part, 67 to 80-percent [127] of waste is removed from operations by transport companies and sent for management to one of the treatment and/or recovery plants authorized in the province [10]. The quality of the vegetable residue that arrives to the processing plants of the province is very low due to its contamination with raffia and other plastic elements from the trellising. This problem has remained unresolved for several years [50,63,96,123] and it constitutes one of the major difficulties in the management of residue and its transformation in organic amendments, i.e., compost/vermicompost, in the agricultural residue management plants [98,128–130].

The main processing plants authorized to treat vegetal debris in the province handle waste with and without raffia [104], although at different costs. The presence of raffia requires different treatment, longer processing times, and the adaptation of the machinery used for crushing vegetal remains. Consequently, the cost of management of these residues increases [63,131–133]. The treatment fee is therefore higher for plant waste mixed with raffia, which results in 15–25-percent of additional cost to the farmer [131,134,135].

Some processing plants crush both vegetal and plastic waste together due to the complexity of separating plastic raffia from plant debris. Once the process of decomposition and maturation of the waste has been completed, it is screened to remove the rest of the non-biodegradable plastic raffia. Other recovery plants remove the raffia once the process of compost maturation is finished [131].

The plastic raffia waste that results from these processes is mixed and polluted with organic matter, so it is stored in the processing facilities and subjected to a conditioning process (drying and cleaning), and a subsequent process of recycling/recovery. In some of the processing plants, a very low percentage of agricultural residue, about 6-percent annually, arrives without polypropylene raffia.

Another problem that processing plants have been facing for several years is the seasonality of the waste production that is concentrated at certain times of the year and exceeds their management capacity. Greater complexity comes when dealing with plant debris that contain plastic raffia [55–59,100]. Vegetal waste from melon and watermelon crops, and vegetal waste from the 90-percent of zucchini crops that are not trellised, are higher quality and are mainly handed to third parties (cattle breeders) to be used as animal beds and, in a smaller percentage, food (3-percent to 22-percent) [63]. Likewise, another part of the raffia free residue or the residue combined with biodegradable raffia is used in the same facilities, but mainly in organic production operations as green manure and compost production (6-percent to 15-percent) [63,99].

3.5. Policies, Strategies and Regulations Promoting the Use of Biodegradable Raffia

Since 2015, one of the Agenda 2030 Goals for Sustainable Development consists of “End hunger, achieve food security and improved nutrition, and promote sustainable agriculture” (ODS 2). This is the principal base for creating worldwide regulatory and management tools to promote sustainable agriculture [9,10] and waste reduction. These tools include the European Green Deal [136], approved by the European Commission 2019, the Europe’s Bioeconomy Strategy (2012–2018) and the recent EU Circular Economy Action Plan *“for a cleaner a more competitive Europe*”, approved by the European Commission (2020) that includes policies about sustainable products [137].

The European Strategy for Plastics, approved by the European Commission in 2018, is part of the measures and priorities that were included in the package of the circular economy adopted by the same institution in 2015. The main goal of this strategy for plastics is to change the way these materials are produced, used, and recycled. The strategy promotes sustainability throughout the value chain to reduce impacts on the environment. The strategy highlights the need to increase the recycling of plastic in agriculture, and to embrace alternatives involving plastic manufactured from biological and sustainable raw materials that contribute to reduce the dependence of fossil fuels [44,76,125].

European Union Regulation No. 1305/2013 from the European Parliament and Council establishes subsidies for rural development through the European Agricultural Fund for Rural Development (EAFRD). Among these aids are those related to “Agri-environment and Climate” and “Organic Farming” [138]. Likewise, the European Union Regulation No. 1306/2013, of the European Parliament and Council, regulates the financing, management, and monitoring of the Common Agricultural Policy [139] and the European Union Regulation No. 1308/2013, of the same institution, which establishes the common organization of the markets for agricultural products and the grants for the fruit and vegetable sector. It also sets out the conditions under which Operational Programmes (OPs) for this sector are financed. Among them, the introduction of goals such as “*environmental measures, particularly those relating to water, and methods of production respecting the environment, including organic farming”* [140].

Based on these regulatory provisions, the Spanish government drew up the National Rural Development Program 2014–2020 (PNDR)[141]. This plan defines the environmental actions and instruments to achieve the environmental and climate objectives. In 2017, the *“National Strategy for Sustainable Operational Programs to be developed by the Organizations of Fruit and Vegetable Producers”* (OPFH) was adopted, which incorporates the actions aimed at environmental objectives, such as the use of biodegradable yarn and/or raffia on the farm, green fertilization by means of farm waste in greenhouse horticulture, and the use of compost of vegetable origin [104]. With regard to biodegradable raffia, the amount of the subsidy was 66-percent of the total cost of the invoice [142] by 2019. In addition, the Spanish Strategy for the Circular Economy, recently approved by the Spanish government, establishes among its main objectives for 2030 a 15-percent reduction in waste compared to that which was created in 2010 [143].

The actions contemplated in the PNDR were included in the Andalusian Rural Development Program 2014–2020 [144]. The Order of 6 April 2017amended the regulations for the Autonomous Community of Andalusia to accommodate funding for the use of biodegradable raffia, the use of compost of plant origin, and green manure [145,146]. Given the low number of applications submitted for the 2017 call, a new public call was made by the Order of 16 February 2018 [147].

Law 7/2007 on Integrated Environmental Quality Management of the Regional Government of Andalusia (Junta de Andalucía) establishes the regulatory framework for the development of environmental policy in this region. This law regulates the tools for environmental prevention and control, which is carried out through the environmental qualification report. This document includes the assessment of the environmental impact to which certain actions and farm infrastructures are subjected to, such as: “Facilities for the agricultural composting of biodegradable waste from agricultural activities, carried out on the farm itself and intended for self-consumption” [148].

Law 3 of 2014 on regulations to reduce administrative burdens on businesses promoted a simplification of authorization regimes, including environmental performance, replacing it with the declaration of responsibility [149]. The implementation of this law took place throughout the Order 1/2006 of the Department of Economy and Knowledge of the Regional Government of Andalusia (Junta de Andalucía) [150]. Farmers who want to carry out compost production from agricultural residual biomass in their own premises for their own consumption must submit a declaration of responsibility to the relevant local authority to guarantee their compliance with the regulations. In this regard, the El Ejido City Council in Almería issued in 2017 the "Ordinance on greenhouses and their environment", regulating the composting of agricultural waste carried out on farms for onsite use [151].

The Order of 29 December 2014for the control of viral diseases in horticultural crops includes mandatory hygienic regulations. The Order states that the vegetable waste intended for self-composting and animal feeding must be free from raffia or other plastic elements or non-biodegradable materials [152]. The 2018 Andalusia Strategy for Circular Bioeconomy has the goal: "To promote and strengthen sustainability practices and better technical alternatives (equipment and machinery) for obtaining, recovery and exploiting biomass resources". The Strategy conforms to the OPFH operational programs, in particular regarding the reduction of waste and the use of biodegradable raffia on the farm [59]. Figure 4 summarizes the resulting policies, strategies, and regulations.

Figure 4. Policy framework, policy instruments and strategies promoting the use of biodegradable plastic (raffia). Source: Authorship.

3.6. Analysis of Alternatives and Main Types of Biodegradable Raffia Marketed

Today, higher grade of raffia and other biodegradable accessories on the market are 100-percent compostable and have been specifically designed for trellising greenhouse crops. They have various characteristics (tensile strength, elasticity, diameter, length) depending on the need of each crop. In Table 3, the main alternatives identified are highlighted, giving priority to Spanish products and especially those from the Province of Almería.

According to information provided by companies marketing biodegradable raffia in Almería, biodegradable raffia consumption has increased. The increase is mainly among farmers who benefit from the agri-environmental aid from the Andalusia Regional Government—Ministry of Agriculture, Fisheries and Rural Development—due to the use of this type of raffia [146]. However, on a general scale its use is extremely low and, in some cases, it only accounts for 1-percent of total raffia sales for greenhouse use (year 2019).

Table 3. Main types of commercialized biodegradable raffia.

Type of Commercialized Raffia	Main Characteristics	Reference
Cellulose/Biopolymer raffia	100% biodegradable. Special for trellising horticultural crops	[63,153,154]
Biopolymer raffia	100% biocompostable product. Bio trellis thread designed for industrial composting. Suitable for organic composting processes.	[155]
1. PLA Raffia: Polylactic Acid Rope 2. Jute cordenka: Cordenka wire and jute strands	100% biodegradable threads PLA rope in horticulture is spun and then braided to improve its strength. It is not sensitive to UV rays.	[156,157]
PLA raffia	Biodegradable raffia	[158]

3.7. Main Causes that Reduce the Use of Biodegradable Raffia and Advantages for Farmers

The main factors that could be related to the low use of biodegradable raffia in protected horticultural crops in the province of Almería.

- **Factors related to product manufacturing and marketing:**
  - Low availability of raw materials (bioproducts) for the elaboration of biodegradable raffia (BR).
  - High cost of raw materials (bioproducts) for the elaboration of BR.
  - Limitations due to field tests.
  - Materials (biomaterials) with long decomposition times.
  - Low market demand, which in turn reduces the supply of BR.
- **Aspects related to the farmer:**
  - Higher cost of biodegradable raffia (BR) than polypropylene raffia (PR).
  - Possible problems due to lesser resistance in BR.
  - Possible problems due to BR humidity absorption.
  - Reduction of BR breaking strength.
  - Low reliability in product quality and mechanical properties because it is relatively new to the market.
  - Limitations in compost production because of the degradation times of the BR.
  - Insufficient awareness/Ignorance of the product and/or the advantages or benefits of its use and existing subsidies.

Another factor to keep in mind when generalizing the use of biodegradable raffia is that it must also be compostable. In many cases, biodegradable raffia is made from materials that take longer to decompose than agricultural biomass. This fact affects the quality of the compost, since it may contain small fragments of bioplastic. It is recommended that raffia be transformed into organic material over a shorter time period to provide nutrients to the soil [121,122].

In practice, the use of biodegradable raffia is far below its potential, as reflected in administrative resolutions granting subsidies for the use of this material. There are only four beneficiaries of the subsidies for the use of this type of raffia for the years 2017 and seven for the year 2018 [159–161]. Access to this aid depends on certain eligibility conditions which must be met throughout the five-year commitment period. In particular, one condition related to the use of biodegradable raffia is a minimum area of 0.1 ha and a commitment to use a minimum of 40,000 linear meters of this raffia per hectare [72]. In this regard, the administration responsible for managing this aid in Andalusia indicates that the low number of applications is not due to the commitments required for the subsidy or to the administrative procedures involved, but rather to the low use of biodegradable raffia by farmers. Applications for subsidies in 2017 and 2018 were for tomato and zucchini crops [159–161].

Main Advantages and Opportunities Linked to the Use of Biodegradable Raffia

The use of biodegradable raffia is an environmentally friendly solution [43]. Its use is linked to a reduction in the GHG and, under certain conditions, it could become a carbon sink throughout its life cycle [121]. For several years there has been an urgent need to replace polypropylene raffia with biodegradable and/or compostable raffia [57,62,96,101,130,145] to ease the management and recovery of vegetable residue, reduce the environmental impact, and improve the sustainability of horticultural systems in Almería [33,63,71,74]. In Figure 5, the main benefits and opportunities of the use of this material for the various horticultural stakeholders are listed.

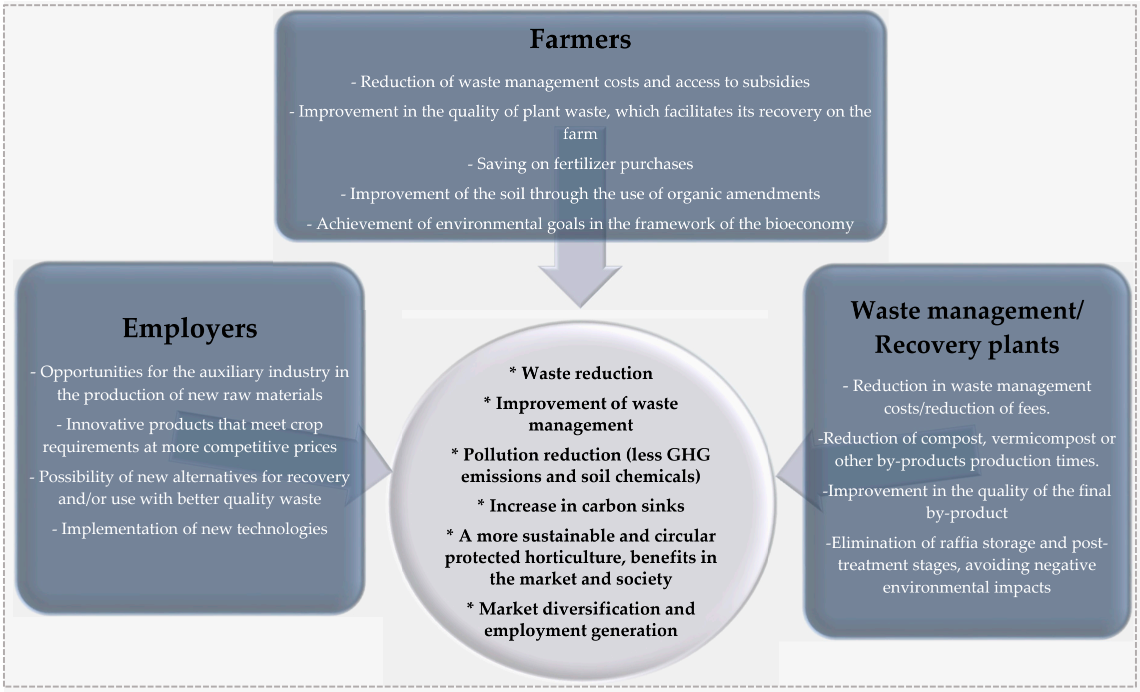

Figure 5. Main advantages and opportunities related to the use of biodegradable raffia. Developed with support from opinions of key players and documentary support [10,33,57,59,63,71,96,101,104,121,130].

3.8. Economic Evaluation of the Use of Biodegradable Raffia Versus Polypropylene Raffia

The annual cost of raffia does not carry significant weight in the total variable cost of the season [162]. To show that biodegradable raffia is a profitable alternative for Spanish farmers in the southeast, we compare the net costs of biodegradable raffia versus conventional raffia. The following considerations were considered:

- Farm size. All the calculations were adjusted to an area of a 1 ha greenhouse, with a typical Almería greenhouse sloping-roof design ("raspa y amagado") [10]. The different varieties of raffia available are grouped into two classes: non-biodegradable (BN) and biodegradable (B). The average prices obtained are 1.7 €/kg for non-biodegradable and 2.6 €/kg for biodegradable raffia.
- An average consumption estimate (kg/ha) was used for each crop based on its weight, planting cycle duration and type of trellising technique (see Table 2). According to our calculations, the highest consumption of raffia per hectare is for the pepper crop. This is followed by cucumbers, eggplants, tomatoes, green beans, and zucchini.
- The average annual generation of biomass for each crop-type in Almería [10] is based on 2019 data. The cost of off-site processing of the residual biomass is based on the average of the rates applied by companies operating in Almería. In all cases, the management of the vegetal residue with raffia is at least 15-percent more expensive than those residues not containing raffia or those containing a compostable one. The results show that the highest quantity of residual biomass

is generated in tomato crops (49 t/ha), followed by pepper crops (28 t/ha), eggplants (27 t/ha), cucumbers (24 t/ha), green beans (23 t/ha), and zucchini (20 t/ha). Average prices for the off-site treatment of the waste are 8 €/t when vegetable remains are mixed with non-biodegradable raffia and 6.8 €/t when the remains are either without raffia or only a compostable one.

- The regional government of the Andalusia Council introduced a maximum subsidy of 600 €/ha per year for those farms that commit to use a minimum of 40,000 m (80 kg on average) of biodegradable raffia during a period of five years. Each applicant farmer must provide the corresponding purchase invoice each year and will be reimbursed up to the aforementioned limit of 600 €/ha. The goal of this subsidy was to encourage the use of biodegradable raffia in years when there was little commercial supply and therefore average prices were much higher than those of conventional plastic raffia. This is a transitional rule, with positive results for the use of biodegradable raffia.

Table 4 shows the calculation of the average costs associated with the use of raffia in a typical greenhouse in south-eastern Spain and it distinguishes the difference between the use of biodegradable and non-biodegradable material.

Table 4. Estimate of average total annual cost per hectare, type of raffia, and type of crop. Year 2019.

	Tomato		Pepper		Cucumber		Zucchini		Eggplant		Green Bean	
Type of Raffia	NB	B	NB	B	NB	B	NB	B	NB	B	NB	B
Average Raffia Consumption (kg/ha)	72.2		83.3		80.0		33.0		80.0		70.0	
Average Price €/kg)	1.7 €	2.6 €	1.7 €	2.6 €	1.7 €	2.6 €	1.7 €	2.6 €	1.7 €	2.6 €	1.7 €	2.6 €
Purchase Annual Cost	126 €	188 €	145 €	216 €	139 €	208 €	57 €	86 €	139 €	208 €	122 €	182 €
Amount of Residual Biomass (t/year) per ha	49		28		24		20		27		23	
Average Cost of External Processing (€/t)	8.0 €	6.8 €	8.0 €	6.8 €	8.0 €	6.8 €	8.0 €	6.8 €	8.0 €	6.8 €	8.0 €	6.8 €
Annual Cost of Waste Treatment	392 €	333 €	224 €	190 €	192 €	163 €	160 €	136 €	216 €	184 €	184 €	156 €
Total Cost at the End of the Season before Subsidy	518 €	521 €	369 €	407 €	331 €	371 €	217 €	222 €	355 €	392 €	306 €	338 €
Aid/Subsidy from the Regional Government	–€	–€	–€	−144 €	–€	−139 €	–€	–€	–€	−139 €	–€	–€
Net Cost after Subsidy	518 €	521 €	369 €	263 €	331 €	233 €	217 €	222 €	355 €	253 €	306 €	338 €

Source: Developed with support documents [10,49,66]. NB: non-biodegradable. B: biodegradable raffia.

The annual cost of biodegradable raffia is 49-percent higher. The difference in the price of biodegradable raffia is reduced if we consider the extra cost involved in treating waste with conventional plastic or non-biodegradable raffia. Thus, the difference in the total annual extra cost for using biodegradable raffia, without considering subsidies, ranges from 0.6-percent for tomato crops to 12-percent for cucumbers. However, when the subsidy is applied, the use of biodegradable raffia could be more profitable in the pepper, cucumber, and aubergine crops.

4. Conclusions

Six of the eight main horticultural crops in the province of Almería (tomatoes, peppers, cucumbers, zucchini, eggplant, and green beans) require a support and guidance system. The different trellising techniques that take place in the province of Almería use mainly polypropylene raffia. Currently, pepper crop utilizes the most raffia, which is 876 t/year. Plastic raffia is non- biodegradable or compostable, which is a problem for its recycling, which creates negative impacts on the environment and can compromise human and animal health. This plastic material pollutes vegetal waste produced in greenhouses. The low quality of this waste restricts its use on farms and in recovery plants. For several years now, policies, strategies, and other regulations have promoted the use of biodegradable and/or compostable raffia.

The use of biodegradable and/or compostable raffia contributes to the purpose of improving the sustainability of horticultural systems in Almería. This practice also means economic advantages for farmers who could avoid the work of separating the raffia and could also take advantage of all vegetable residue due to its high potential of circularity or for its reuse in farming operations. Such action also reduces GHGs. The use of organic fertilizers prevents contamination by nitrates and also means savings for the farmer by reducing the consumption of these chemical compounds. Even if this waste were not used on the farm itself, the management fees through a third party would be lower, meaning some economic advantages for farmers.

There are various barriers for the use of biodegradable raffia in Almería, principally cost. However, there is currently a significant supply of raffia and other biodegradable fasteners on the market made of different materials specially designed for the support of greenhouse crops. These materials have characteristics similar to polypropylene raffia and have been adapted to the needs of different types of horticultural crops.

Many of the materials from which this type of raffia is made have been improved to facilitate the recovery of residual agricultural biomass and to expand the alternatives for its use. In addition to being biodegradable, they are compostable in a similar period to that of plant remains. Therefore, using this type of raffia also offers the opportunity of business diversity and the economic strengthening of the horticulture industry in the province. It is an opportunity for the production of new raw materials and the manufacturing of innovative products, which meet the requirements of the crops at more competitive prices. Government financial aid is a strategy that allows the implementation of these measures. Subsidies must be complemented with socialization campaigns and technical assistance to promote farmer awareness.

The higher cost of biodegradable raffia, on average, is partly offset by the lower cost of treating the residual biomass. In the case of crops where the subsidy applies (pepper, cucumber, and eggplant), farmers profit by using biodegradable raffia rather than conventional, plastic and non- biodegradable raffia. Despite the transitory nature of the subsidies for biodegradable raffia, we recommend that the aid be modified to cover all crops.

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