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ORIGINAL ARTICLE

Exploring alternative solutions for sustainable waste management in the horticultural greenhouse sector

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Abstract

Intensive agriculture is increasingly adopted due to its high productivity. However, it generates significant amounts of waste that are potentially harmful to the environment. For example, greenhouse horticulture is commonly practised in several Mediterranean countries and generates waste that is difficult to manage, especially plastics. Unfortunately, current waste management practices, such as incineration, landfilling or dumping, are often not sustainable. However, there are possible alternative solutions for sustainable waste management. Therefore, the objective of this article is to present alternative systems based on different models of cooperative management of waste generated in the horticultural greenhouse sector. Five alternatives were analysed in terms of their economic, social and environmental sustainability using expert knowledge processed with the Analytic Hierarchy Process (AHP) method. The results show that there are alternative solutions to manage waste in a more sustainable way in the horticultural greenhouse sector, such as establishing collaboration between cooperative and managers, and the cooperative becoming the waste manager. None of the cooperatives in the region studied have currently implemented these two options. By adopting these alternative solutions, cooperatives can play a key role in promoting sustainable waste management practices in the horticultural greenhouse sector.

Keywords Waste management · Horticulture · Greenhouses · Sustainability · AHP

Introduction

Agriculture is a key economic sector in Spain, contributing 2.2% to the country's Gross Domestic Product (GDP), significantly more than the EU average (1.3%) [1]. In particular, Spain is the largest producer of horticultural products within the EU, with 17.5% of total EU production [2]. Southern Spain, and especially the province of Almeria, leads the country's horticultural production. In fact, the highest concentration of greenhouses in Europe is in Almeria, which had 32,554 ha of greenhouses in 2020 [3–5]. This large area of greenhouses in Almeria is sometimes referred to as the "plastic sea". Almeria produces tomatoes, peppers, onions, watermelons, lettuce and other horticultural products that are mainly exported to other European countries. These agricultural products are often produced under intensive greenhouse practices.

One of the problems associated with horticultural production in greenhouses is the large amount of waste generated, e.g. greenhouse structures and plastic films [6, 7]. Plastic used as protective material accounts for about 6% of the waste produced in greenhouses, while 94% is vegetal waste, which is mostly plant remains. It has been estimated that around 90,738 tonnes of non-vegetal waste, with a volume of 187,050 m^3, are produced each year in horticultural greenhouses in Almeria [8, 9]. Covering structure and disinfection plastic represent the largest amount of non-vegetal waste by weight (43% and 23%, respectively), and by volume (27% and 22%, respectively) [8], followed by steel for the greenhouse structures and small amounts of textiles, wood and cardboard [10]. The large amount of plastic waste generated in agriculture also occurs in other geographical areas, such as the coastal regions of southern Italy [7, 11], Greece [12] and Cyprus [13]. This agricultural plastic waste may break

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up into macroplastics, microplastics and nanoplastics, potentially polluting the environment and even entering the food chain [14]. To collect data more efficiently on this issue, Geographic Information Systems (GIS) are increasingly used for the mapping and quantification of agricultural plastic waste [15–17]. A recent study with GIS in Italy, Spain, Greece and Portugal found that Andalusia is the highest contributor to agricultural plastic waste, due to the extensive use of agricultural plastic in Almeria and Jaén [12].

The management of this non-vegetal waste, especially plastic waste, is problematic, as these materials are often not recyclable and often end up in incineration, landfill or even dumped in the immediate vicinity of greenhouses, with consequent damage to the environment. Farmers are now more aware of the negative consequences of these practices. In addition, increasingly stringent EU and national regulations are pushing farmers to look for more sustainable solutions to manage this waste. An example of recent developments in waste management policies can be seen in Spanish legislation, which has introduced stricter regulations for the practice of landfilling, a common method of disposing of waste materials [18]. In addition, the EU has established landfilling as the least preferred method of waste management [19]. Garcia-Garcia et al. [10] identified the following factors as having the greatest impact on non-biodegradable waste management in horticultural cooperatives: inconsistent regulatory frameworks, lack of (individual or collective) systems for waste management, deficient documentation and poor traceability. Consequently, research is currently underway to identify alternative solutions for the management of plastic waste generated in greenhouses, such as the use of these materials for other applications [20] and the substitution of plastic materials in greenhouses with biodegradable and compostable alternatives [21].

In the particular case of Almeria, Duque-Acevedo et al. [22] studied waste management strategies followed in greenhouses, focusing on biomass, which is also generated in large amounts in greenhouses. The most common strategy is to send the waste to external waste management companies and authorised recycling plants. Secondly, the waste is used for animal feed. A small proportion of the waste is used as green fertiliser by farmers. Finally, a very small percentage is composted in greenhouses. Currently, there is no integrated system for the management of greenhouse plant waste in Almeria [22]. Each farmer manages their waste independently with the main objective of reducing management costs. This reduces the traceability of the waste management system and increases the likelihood of inadequate waste management. Furthermore, greenhouse farms in Almeria are generally small and family-run, with an average area of 1.9–2.6 ha and an average of 5 workers per farm [8]. This is an additional obstacle for the adequate management of waste, together with its seasonal nature and, above all, its high cost. However, alternative solutions to manage waste in a more cooperative way exist and are expected to offer several advantages over current individualistic approaches.

Indeed, in Almeria, horticultural farmers are mainly grouped in cooperatives, which could allow for a more efficient and cost-effective waste management. Cooperatives could bring their expertise in waste management, which would allow them to develop waste reduction, reuse and recycling strategies. In addition, cooperatives can help farmers access waste collection services, as well as provide technical and financial assistance for the implementation of waste management practices. Cooperatives can also facilitate the implementation of integrated waste management systems, which are necessary to ensure that waste is handled and disposed of in an environmentally responsible manner. In addition, cooperatives can help reduce the costs associated with waste management, allowing farmers to allocate resources to other areas of their business.

In this context, the objective of this article is to explore alternative management systems of non-vegetal waste for horticultural greenhouse cooperatives and to evaluate their economic, social and environmental sustainability. The Analytic Hierarchy Process (AHP) methodology, widely recognised as an effective method for evaluating complex multi-criteria decision-making (MCDM) problems, is used to build a framework for this evaluation. The AHP methodology allowed the comparison of alternative waste management systems with the conventional practice, using the knowledge of experts in the sector. The economic, social and environmental sustainability of four alternative waste management systems were evaluated and compared with the conventional practice in order to determine the most sustainable option. The ultimate aim of the research is to provide information on the feasibility of sustainable waste management systems for horticultural greenhouses in Almeria, and to propose a series of policy recommendations to promote the spread of the most sustainable waste management practices. The results are expected to be valuable to policy makers, greenhouse farmers, waste management companies and other stakeholders as they seek to address the challenges associated with unsustainable waste management practices in the region. In addition, this study aims to contribute to the wider field of sustainable horticulture by providing a model and methodology for evaluating sustainability and alternative horticultural waste management systems that could be applied in other regions and farming systems.

Methodology

This section outlines the methodology used to analyse alternative waste management systems, including the selection of indicators and the application of the AHP. It must be noted that there exist a number of MCDM methods, each one with their advantages and disadvantages. For solid waste management, the most relevant ones are AHP, Multi-Attribute Utility Theory (MAUT), Preference Ranking Organization METhod for Enrichment Evaluations (PROMETHEE), ELimination and Choice Expressing REality (ELECTRE) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). AHP is the most common MCDM method to study most solid waste management systems [23, 24], and, specifically, agricultural waste management [25]. This is mostly due to its versatility and the possibility of comparing different criteria and stakeholders' preferences. Based on this, we chose AHP as the MCDM method in this case study.

Alternative cooperative waste management systems

The alternative waste management systems considered in this study are based on different levels of partnership between the cooperative and other members. In order to identify alternative waste management systems, a combination of literature review was firstly used as a first approach to understand the state of the art in waste management in the horticultural greenhouse sector, followed by an Open Innovation Lab (OIL) with agents of the sector and experts. The literature review provided information on the most widespread waste management practices in the agricultural sector and relevant legislation (e.g. [3–5, 7, 8, 14, 18, 19]). The OIL took place on 23rd May 2019 and provided a platform for diverse stakeholders from the sector to collaborate and identify alternative waste management systems. Thirty people participated: five from the project organisers, eight from sector companies and horticultural producers, four experts in agricultural management, six from innovative solution providers, two from research and development centres and five from public entities and policymakers. During the OIL, participants shared insights on current practices and potential obstacles and challenges to adopt alternative systems. This collaborative effort aimed to gather valuable information and generate innovative ideas to facilitate the implementation of more sustainable practices.

Following the procedure explained above, it was found that the conventional practice is that the cooperative is not involved in the waste management activities of its members. Based on the literature review and the OIL, the following alternative systems, with an increasing level of complexity in terms of waste management and cooperative involvement, were proposed:

Alternative 0. Cooperative not involved in waste management: The cooperative does not participate in the waste management activities of its members. This is the conventional practice.

Alternative 1. Cooperative agreements with transport company: The cooperative establishes agreements with an authorised transport company that is responsible for collection from the farm, transport and delivery of the waste to the management plant. This alternative includes a collection system for agricultural packaging, managed by the non-profit organisation SIGFITO, as well as the management of non-returnable containers by hazardous waste managers.

Alternative 2. Cooperative agreements with management plants: The cooperative establishes agreements with waste management plants, so that farmers deposit their waste at the facilities of these companies. This alternative includes a collection system for agricultural packaging, managed by SIGFITO, as well as the management of non-returnable packaging by managers of hazardous waste.

Alternative 3. Collaboration between cooperative and managers: The cooperative coordinates a system that is executed by waste managers. The cooperative organises the collection to facilitate management and reduce costs, registers the waste managed and ensures the correct management of the waste, in compliance with the current regulations. Furthermore, the cooperative collaborates with waste managers to develop cost reduction strategies, such as optimising collection routes or identifying more efficient methods to manage waste. This alternative is not currently employed by any cooperative in the region.

Alternative 4. Cooperative manages waste: The cooperative becomes the waste manager, assuming responsibility for the collection, transportation, treatment and disposal of its own waste. This option eliminates the need to contract a third party for the management of waste. Furthermore, this option enables the cooperative to assume a more prominent role in the waste management process, thereby facilitating the implementation of environmentally responsible waste management practices. It is essential that the cooperative possesses the requisite infrastructure, equipment and personnel in order to effectively manage its own waste. This alternative is also not currently applied by any cooperative in the region.

Experts were consulted on the possibility of the cooperative assuming the role of the final recycler as an additional alternative for implementation. For example, the cooperative could produce plastic pellets. Nevertheless, this option was deemed technically unfeasible in the near term due to the substantial initial investment costs and the limited size of the cooperatives. Consequently, it was excluded from further consideration.

Sustainability indicators

The sustainability indicators used to evaluate the performance of the five waste management alternatives were defined through a combination of literature review and the OIL, as described in "Alternative cooperative waste management systems". A selection of relevant journal articles that analyse sustainability assessments in agriculture was used to propose the indicators in the three dimensions of sustainability [26–29]. During the OIL, the research team discussed the purpose of each indicator identified in the literature, its relevance to the specific context of the study and how it could be used to measure the sustainability of the waste management alternatives in horticultural greenhouses. This enabled the identification and refinement of a set of comprehensive, relevant and meaningful indicators that could be used to measure the economic, social and environmental performance of waste management alternatives. These indicators are defined below.

Economic indicators:

Overall profitability for farmers: Measures how the alternatives affect the overall profitability obtained. It is calculated by subtracting costs from revenues.

Strategic positioning and competitiveness in the market: Measures how the adoption of innovations can improve the company's position in the medium and long term.

Intrinsic product quality: Refers to the quality attributes of the food produced by the farmer.

Diversification of economic activities related to waste management in the region: Refers to the presence of diversified economic activities related to waste management in the region.

Social indicators:

Direct and indirect employment: Quantifies the number of jobs generated on the farm and in other related sectors.

Intergenerational continuity of agrifood activities: Measures the level of continuity of economic activity over time due to the continuity of human capital.

Health of consumers and public health: Assesses the hygienic and sanitary conditions of products produced by farmers.

Health conditions of workers: Assesses the hygiene and health conditions of farmers/workers.

Environmental indicators:

Biodiversity of flora and fauna: Measures the number and variety of living things in the environment.

Quality of groundwater and surface water: Assesses groundwater and surface water contamination.

Soil fertility/quality and control of soil erosion: Measures soil fertility and quality as well as the degree of soil erosion.

Climate change abatement: Measures greenhouse gas emissions.

Landscape quality: Refers to the aesthetic quality of the region's landscape.

Analytic hierarchy process

AHP was used to evaluate the performance (also known as priority) of the different alternatives for each indicator considered. AHP is a multi-criteria decision-making technique developed by Saaty [30] that allows solving complex decision-making problems involving multiple, usually conflicting, criteria and stakeholders. It does this by prioritising a set of alternatives based on their performance with respect to a set of criteria and the overall objective or goal.

The structure of the AHP model for this study is shown in Fig. 1. It includes the alternatives and indicators defined in the previous subsections. The five alternatives at the bottom of the figure are evaluated in terms of their performance (or priority) with respect to each indicator placed above. The performance on these indicators is then used to prioritise the alternatives in the economic, social and environmental domains. Finally, the global performance of each alternative is calculated, allowing the alternatives to be ranked according to their performance in achieving the goal.

The mathematical steps involved in building the AHP model are explained in more detail below.

1. Survey to experts: For each element of the hierarchy on which other elements depend, the local priorities or weights (ω_L) of these sub-elements with respect to their respective parent node must be evaluated in terms of performance or priority. Equation 1 must be satisfied for each node:

$$0 \leq \omega_{L(i)} \leq 1, \text{ and } \sum_{i=1}^{n} \omega_{L(i)} = 1, \quad (1)$$

where $\omega_{L(i)}$ is the local priority of an element i with respect to its parent node, and n is the number of elements that depend on the parent node.

The evaluation was conducted through an online survey from January to March 2020, relying on expert knowledge. The technical nature of the information required and the dearth of prior ad hoc hard data on the majority of topics examined necessitated the use of expert knowledge. Nine experts were asked to evaluate the model by direct rating [31–33]: four individuals from public research organisations, four from the sector and one from public administration. Specifically, a rating scale was used to evaluate the local priorities, ranging from 1 (very low priority) to 9 (very high priority), with 0 for no priority [34, 35]. The experts individually filled in the sections of the surveys about which they had knowledge and experience. The local priorities of the elements (e.g. waste management alternatives) with respect to their parent node (e.g. profitability) were calculated by

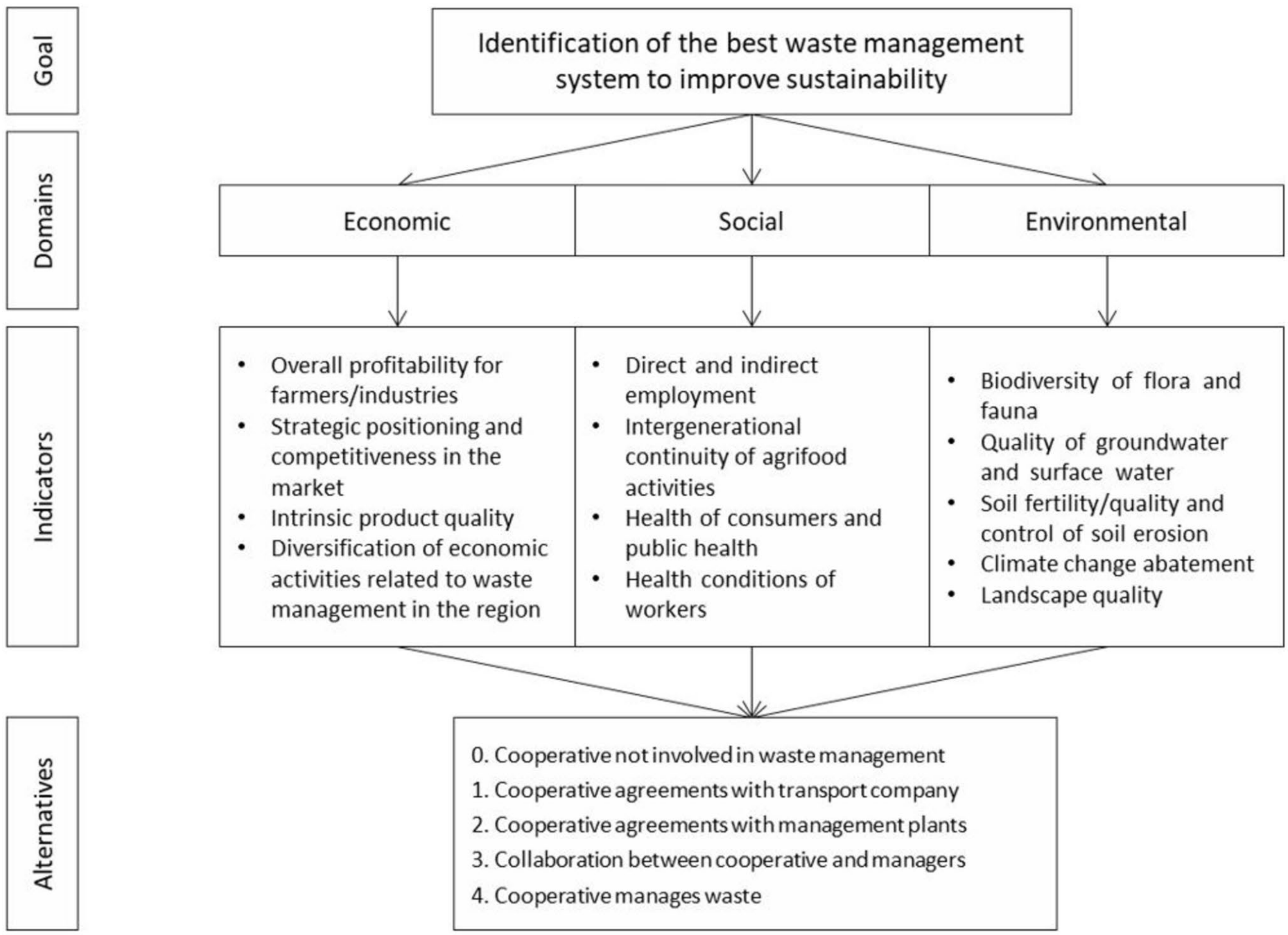

Fig. 1 Structure of the AHP model

normalising the rating values stated by each expert to these elements, so that they sum to 1.

2. Aggregation of individual priorities: Individual local priorities were condensed into aggregated local priorities. Various aggregation methods exist [36]. In our study, they were calculated using the arithmetic mean of the individual priorities (AIP) method (Eq. 2), which is recommended when the group (in this case, experts) is assumed to act as separate individuals [37, 38]:

$$\omega_{i,j(\text{aggr})} = \sum \forall_{i,j} \omega_{i,j(e)} / E, \tag{2}$$

where $\omega_{i,j}$ is an element of a node, e is an expert and E is the number of experts.

3. Synthesis of priorities: Finally, the alternatives were prioritised according to their performance with respect to the goal (global priorities, ω_G) or any intermediate node of the decision hierarchy (final priorities, ω_F). The global and final priorities of the alternatives were calculated from all local priorities of the sub-objectives and alternatives depending on the goal or intermediate node, respectively, by weighted addition [39]. The final priorities of the alternatives with respect to a particular main criterion of our AHP model (e.g. the economic dimension) were calculated with Eq. 3:

$$\omega_{F(Ak)} = \sum_{i=1}^{I} \omega_{L(Ak/i)} \times \omega_{L(SOi)}, \tag{3}$$

where $\omega_{F(Ak)}$ is the final priority of alternative k, $\omega_{L(Ak/i)}$ is the local priority of alternative k *with respect to* the sub-objective i into which the main criterion has been broken down (e.g. "profitability" sub-objective), $\omega_{L(SOi)}$ is the local priority of sub-objective i *with respect to* the main criterion (e.g. economic dimension) and I is the number of sub-objectives (e.g. economic indicators) depending on the criterion.

Results

This section presents the results of the evaluation of the waste management alternatives in the three dimensions of sustainability. It shows the performance of the alternatives for each indicator and the priorities of the alternatives in the three dimensions of sustainability. Finally, it shows the performance of the alternatives at the global level. This allows a holistic view of the sustainability performance of the alternatives. It must be noted that the performance units are dimensionless, since the units for the indicators are not comparable and the priority was used for the comparisons.

Performance of alternatives for each indicator

The performance (or priority) of the different alternatives is shown in Fig. 2. The results differ significantly between the alternatives. Alternative 3 "Collaboration between cooperative and managers" scores the highest on three economic indicators (i.e. "Overall profitability for farmers", "Strategic positioning and competitiveness in the market" and "Intrinsic product quality") and on all environmental indicators (i.e. "Biodiversity of flora and fauna", "Quality of groundwater and surface water", "Soil fertility/quality and control of soil erosion", "Climate change abatement" and "Landscape quality"). For all social indicators, such as "Direct and indirect employment", alternative 4 "Cooperative manages waste" scores the highest. Alternative 0 "Cooperative is not involved in waste management" scores the lowest on all indicators, which means that the conventional practice is the least sustainable.

Performance of alternatives in the three dimensions of sustainability

Figure 3 shows the performance of the waste management alternatives in the different dimensions of sustainability. Alternative 3 "Collaboration between cooperative and managers" performs best in the economic and environmental dimensions, while alternative 4 "Cooperative manages waste" performs best in the social dimension. However, the priorities of these two alternatives are similar. The remaining alternatives score lower, and in the following decreasing order for the three dimensions: alternative 2 "Cooperative agreements with management plants", alternative 1 "Cooperative agreements with transport company" and alternative 0 "Cooperative not involved in waste management". Again, the conventional practice (alternative 0) scores the lowest, which means that this practice is the least sustainable.

Performance of alternatives at global level

Figure 4 shows the priorities of the alternatives at the global level. The performance of alternative 3 "Collaboration between cooperative and managers" is the highest. The priority of alternative 4 "Cooperative manages waste" scores very similarly, which means that it is also a good alternative. Overall, the worst performance is that of the conventional practice (alternative 0).

Discussion

Based on the performance of the different alternatives, public policies should prioritise sustainable practices, such as collaboration between cooperative and waste managers, and promote initiatives that allow the cooperatives to manage waste, as this will improve sustainability. In addition, policies should discourage conventional practices, as they are the least sustainable.

The main recommendation of this study is to apply alternative 3 "Collaboration between cooperative and managers", based on its higher overall performance. However, alternative 4 "Cooperative manages waste" outperforms alternative 3 in the social dimension. Therefore, the selection of one alternative over the other also depends on the weights that a particular cooperative may give to each of the three dimensions of sustainability, which may differ from those established by the experts consulted. Consequently, in the event that a cooperative deems the social dimension to be of particular significance in the context of its own particular case, then alternative 4 would outweigh alternative 3. In any case, both alternatives significantly outperform the current alternative 0 "Cooperative not involved in waste management".

There are other aspects to be considered when deciding which alternative is most suitable, e.g. its technical feasibility. The implementation cost of each alternative is expected to be directly correlated to its technical feasibility. Based on the expert consultation, it was established that alternative 0 "Cooperative not involved in waste management", alternative 1 "Cooperative agreements with transport company" and alternative 2 "Cooperative agreements with management plants" show a high technical feasibility. On the other hand, alternative 3 "Collaboration between cooperative and managers" and alternative 4 "Cooperative manages waste" currently show medium and low technical feasibility, respectively. This further supports the general recommendation of

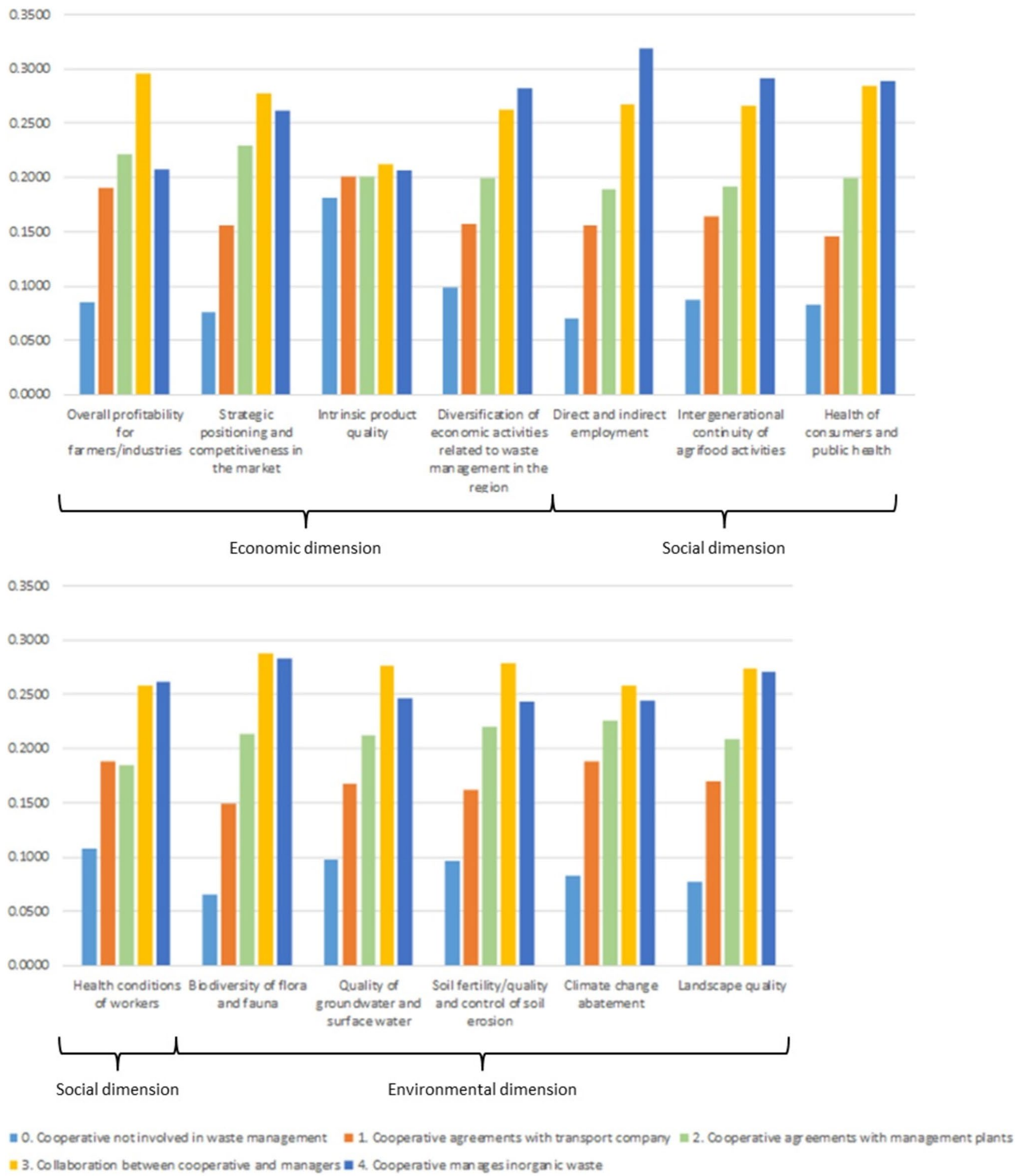

Fig. 2 Average performance of the alternatives on the indicators

this study to prioritise the implementation of alternative 3 "Collaboration between cooperative and managers".

If alternative 3 "Collaboration between cooperative and managers" is applied, the cooperative would be in charge of setting up a space for waste reception and organising waste collection, finding a waste manager for each type of waste produced, establishing collaboration agreements with waste management companies and keeping a waste

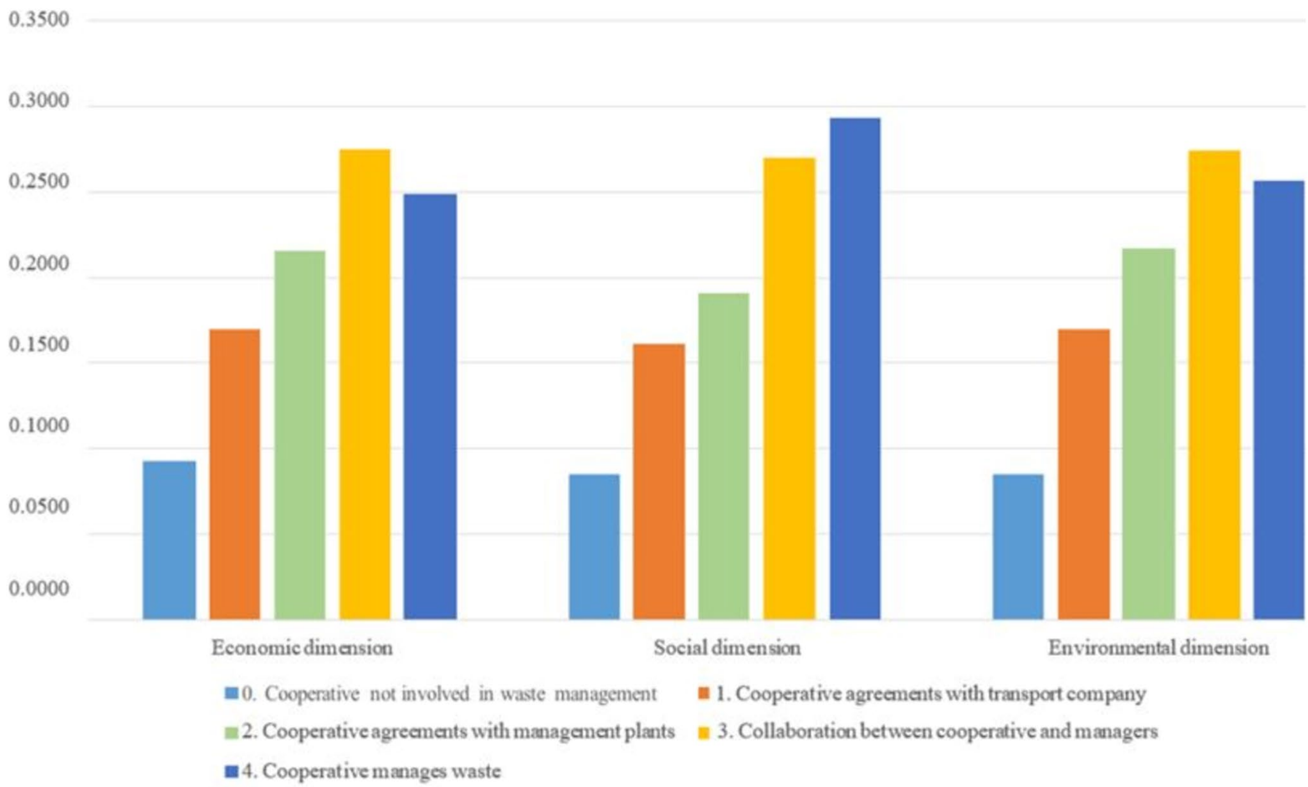

Fig. 3 Average performance of the alternatives in the three dimensions of sustainability

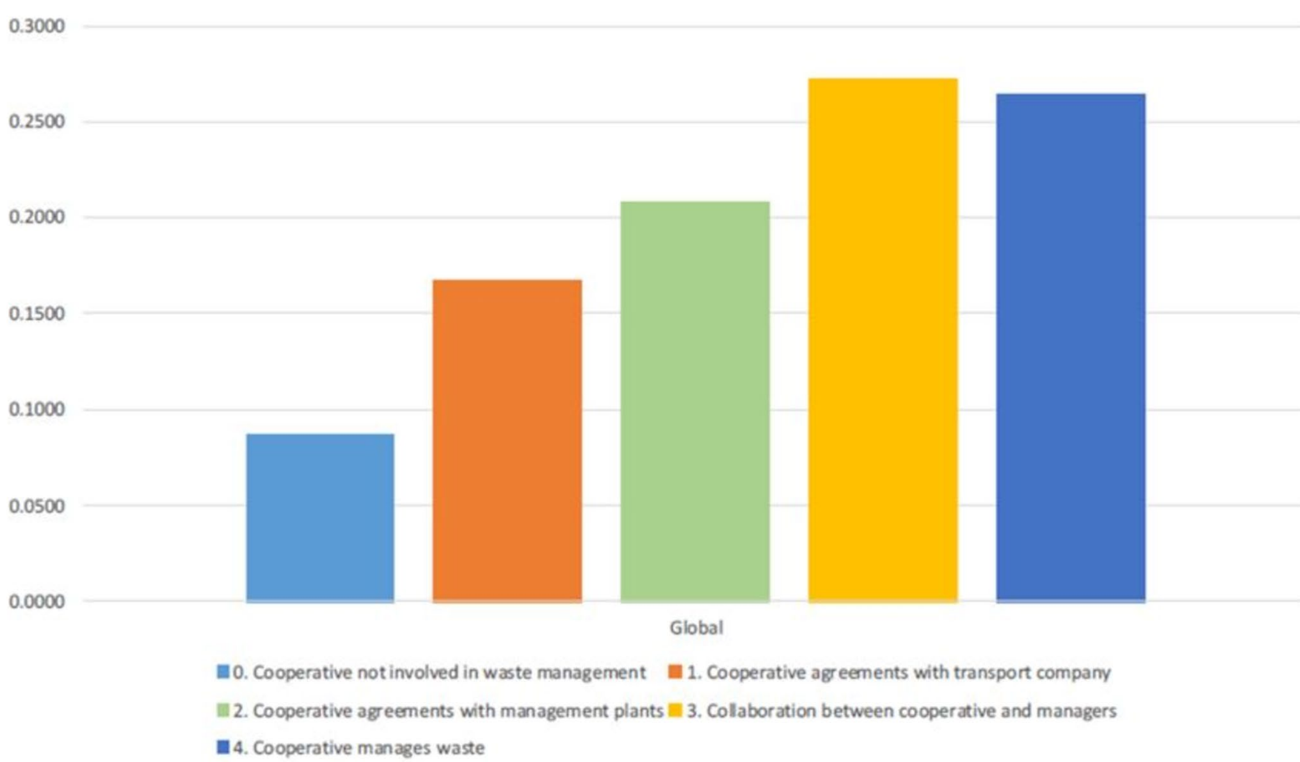

Fig. 4 Average performance of the alternatives at the global level

register, in compliance with current regulations. The cooperative should establish a monthly fee for its members to cover these costs, depending on the amount of waste generated.

To overcome the reluctance of cooperatives to implement alternative solutions for their waste management, it is recommended to use promotional factors in the adoption of such alternatives. Such promotional factors should include increased awareness in the agrifood value chain regarding waste generation, economic benefits based on economies of scale and the willingness of producers and other organisations to improve waste management.

Finally, although the framework proposed in this article has been specifically designed to study management of non-vegetal waste from greenhouses, it could be easily used to analyse vegetal waste from greenhouses too. Similarly, the indicators were deemed to be especially relevant for the horticultural sector in Almeria (as confirmed by the OIL), but they could be used to assess the sustainability performance of greenhouses in other geographical locations. Other management systems could also benefit from a similar framework, but the list of alternatives proposed must be amended.

Conclusions

The management of non-vegetal waste generated in horticultural cooperatives is a crucial issue for sustainability. This paper analysed different alternative systems that can be adopted by these cooperatives to manage their waste in a more sustainable way. These alternatives were analysed in terms of their economic, social and environmental performance. The results indicate that the involvement of cooperatives in waste management can improve sustainability in different dimensions. However, not all alternatives are equally effective and there may be some trade-offs between economic, environmental and social performance. Collaboration between cooperative and waste managers is particularly desirable because of its greater sustainability and feasibility. Waste managers can provide technical assistance and training to cooperatives to improve their waste management practices. By adopting these alternative solutions, cooperatives can play a key role in promoting sustainable waste management practices in the horticultural greenhouse sector.

To strengthen the adoption of more sustainable waste management practices in the greenhouse horticulture sector, the following policy recommendations are proposed:

1. Promote collaboration between cooperatives and waste managers through incentives and regulations: Government policies can promote collaboration between cooperatives and waste managers by offering incentives such as tax breaks, subsidies or grants. Regulations can also be introduced to ensure that waste managers provide technical assistance to cooperatives to improve their waste management practices.
2. Support cooperatives in managing their own waste through capacity building and technical assistance: Governmental and non-governmental organisations can provide cooperatives with technical assistance and capacity building to improve their waste management practices. This can include training in recycling and reuse, waste segregation and composting.
3. Foster a culture of sustainability among cooperatives and their members through education and awareness: Education and awareness programmes can be conducted to promote sustainable waste management practices among cooperatives and their members. This can include workshops, training sessions and awareness campaigns to highlight the importance of waste management for sustainability.

Furthermore, this study makes a contribution by applying the AHP methodology and creating a framework for evaluating the sustainability of alternative waste management practices in the horticultural sector and identifying the optimal solution. By providing a comprehensive framework for assessing sustainability, this research can inform decision-making processes and facilitate the development of more sustainable waste management strategies. Ultimately, the framework presented in this research has the potential to drive improvements in sustainable horticultural practices and advance the broader field of agricultural sustainability. Future research can build on this framework to refine and expand the range of applications, enabling more effective and comprehensive sustainability evaluations in horticulture and other agricultural sectors, as well as an optimisation of their performance.

Finally, it is recommended that future research should explore additional strategies to improve the sustainability of waste management practices in greenhouses. For example, alternative materials such as compostable stakes instead of plastic stakes and biodegradable plastic films instead of traditional plastic films may provide new avenues for effective waste management. These approaches should be explored and tested to optimise waste management, reduce waste generation and minimise the negative environmental impact of greenhouse operations.

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