Repeated Plant Debris Reutilization as Organic Amendment

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Greenhouse agriculture typically generates large amounts of waste with plant residue (agricultural biomass) being the most abundant. This residue is generated on a seasonal basis, which complicates the external management of the material. Recently, the European Union (EU) has been implementing a policy based on sustainability through the circular economy that seeks to minimize waste generation. The effect of reusing 3.5 kg·m-2 tomato plants from the previous season as the only fertilizer versus no fertilization and inorganic fertilization in 215-day tomato cycles after transplanting was studied in this trial. The study was carried out during three seasons in greenhouse agriculture in Almeria (Spain) with the repeated use of the solarization technique. The plant debris had similar production results during two of the three seasons and fruit quality parameters were similar to inorganic fertilization. In addition, some physicochemical variables improved and the biological depressive effect of solarization was mitigated. The results suggest that the reuse of the tomato plant debris as the only fertilizer could be an alternative to conventional fertilization under the conditions tested.

Keywords: circular economy ; bioeconomy ; waste management ; tomato crop ; agriculture ; organic fertilizer ; horticulture ; soil fertility

1. Introduction

The province of Almeria (Spain) is the part of the world with the highest concentration of greenhouse surface [1][2][3][4]. The implementation of this intensive agricultural production system has increased the productivity and profitability of its crops in just 60 years [5] while transforming Almeria into one of the major suppliers of fruit and vegetable products in the EU. The agricultural development of the area has enriched the socioeconomic structure of the province [5][6]. This is a production system that, due to the climatic conditions of the area and the characteristics of its greenhouses (*e.g.*, Almeria or “Raspa y Amagado” type), does not require climatic correction [7][8]. This fact, along with various agroecological techniques and commonly used cultivation methods (*e.g.*, biological control, grafting, integrated pest and disease management) makes this production system one that requires less energy consumption than other similar agricultural systems [9] and also improves the sustainability of the agrosystem under the production principles of different types of certifications [7]. However, there have also been impacts on area ecosystems (*e.g.*, loss of biodiversity, erosion, overexploitation, and eutrophication of aquifers, etc.) that seriously threaten the environmental sustainability of the production model. This requires the formulation of various corrective measures to reverse the situation [4][10][11]. One of the main causes is inefficient management of agricultural waste. This is an endemic problem within this production system that caused a sanitary crisis at the end of the 20th century that ended up forcing public intervention [4].

European regulations enforce the management of agricultural waste through its transformation into by-products when possible (*e.g.,* livestock feed, bioenergy, organic amendments, substrates, plastics, plastic pellets, etc.) [2][12]. The legal bases are founded on the principles of the circular economy and the bioeconomy, which favor the implementation of EU sustainability strategies applicable throughout its productive agriculture sector [13][14][15][16]. The implementation of these strategies is one of the collective changes to be made by the Almeria Model [10], which presents abundant opportunities to apply the principles of the circular economy in its production phases [4][17].

Plant debris (agricultural biomass) are considered a wasted by-product in some European agricultural systems [15]. The location and seasonality of their production, as well as a lack of space on some farms, inadequate transport logistics, the mixing of plant debris with plastic trellising inputs, and the poor phytosanitary condition of the material make its management difficult [18]. There is also a failure to maintain stable inputs for the transformation processes of the plant element [17], which does not justify the investment in building external treatment centers in certain locations while also transport costs increase [18]. In the Almeria model, 1.8 million tons of plant debris are generated annually, 80% of which is generated in only three months (February, May, and June) [18]. Some of the alternatives evaluated to mitigate this problem (transformation into bioenergy or animal feed) do not offer a viable option compared to the predominant management of the by-product [4][19], which currently consists of its delivery to an agent authorized by the administration to transform the plant material into compost [18]. However, several studies have posited self-management of plant debris by farmers as a suitable reuse process [4][7][17][20][21][22]. This is a great opportunity for the Almeria Model to apply the principles of the circular economy and the bioeconomy, which so far have not been extensively implemented in Almeria greenhouse agriculture [7][17][18]. Through this management methodology, it is possible to generate economic [4] and productive [20][21][22] benefits since its use as an organic amendment makes it possible to reduce and even eliminate external inputs of fertilizing materials during the crop cycle [20][21] thanks to the mineral elements associated with these plant by-products [23].

This material can also be used to improve soil fertility [24][25][26], which is defined by its physical, chemical, and biological components [27]. Specifically, the addition of organic amendments has a positive influence on these components even when their introduction is carried out through the solarization technique [20][28][29][30][31][32]. This soil biodisinfection protocol combines the effects of solarization [33] and biofumigation [34] and is traditionally used as an alternative to chemical control of soil pathogens [35][36][37][38]. Thus, the biological component is considered essential for maintaining and improving the health and fertility of agricultural soil [39]. It is, therefore, essential to support actions to protect soil biodiversity and promote its sustainable use and management through the application of sustainable practices [40][41].

2. Current Insights

This research, which was carried out over three years, aimed to evaluate the effects of the repeated supply of tomato plant debris from the previous season versus the use of inorganic cover fertilization and no fertilization on tomato production and crop quality; physical, chemical, and biological soil variables that determine soil fertility, and on the vigor of tomato and cucumber seedlings grown under controlled conditions. In all cases, the solarization technique was applied during the summer months before the start of cultivation, and production cycles were of 215 DAT. Previous research concluded that the addition of tomato plant debris was sufficient for the correct development of a greenhouse tomato crop when production cycles were lower than 170 DAT. This achieved the same yield as when applying a conventional inorganic fertilizer while also maintaining the main organoleptic properties of the fruit [20][21]. However, the aforementioned study included two crop cycles and it did not report information on the effects on soil parameters or the evaluations in a controlled environment chamber using bioassays that help to better interpret the effects on these soil parameters which determine its fertility. In addition, greater precision has been achieved concerning the analytical findings. The results of the three years of testing in the present study suggest that exclusive fertilization with tomato plant debris produces a yield and crop quality similar to that obtained with traditional inorganic manure in production cycles of 215 DAT (Figure 1). Several authors have reported a similar result when they analyzed the production of tomato crops with only organic fertilizer (compost, bone meal, blood or hoof meal, chicken, sheep or turkey manure, and plant debris) versus conventional fertilization, both with or without using pre-transplant solarization and conventional fertilization [42][43][44][45][46][47] to obtain a tomato fruit of similar quality [43][44][45]. Some investigations have also reported decreases in the production of a bell pepper crop nourished with tomato plant debris and compost compared to the conventional crop. It should be noted that a small amount of inorganic fertilizer was added to the organic fertilization and that the solarization technique was not used [22]. Thus, the technique of soil solarization combined with organic amendments, also known as biosolarization, has resulted in increases in the production of different crops. Nonetheless, the effects reported in these studies have been mostly the result of the control of pathogens that limit the correct development of the plants and in crops that have incorporated inorganic nutrition [35][36][37][38][48]. It should also be noted that the soil biosolarization technique can have an influence on soil fertility [28][29][30][31][32][49] in conjunction with the control of soil pathogens. The use of the biodisinfection technique seems to favor the decomposition of organic amendments, in our case of plant debris from the previous crop. The application of this technique could help to decrease the time necessary for the decomposition of the material. This would provide the plants with a higher content of nutrients needed for growth in a shorter time [29][32]. In addition, the use of the solarization technique helps to limit pests and diseases that may be associated with plant debris incorporated into the soil [20][50]. The presence of these organisms in combination with plant material is normal after long-term production cycles, and it is essential to avoid their expression during the following production cycle in order not to limit crop production. The repetition of non-fertilization resulted in a continuous decrease in final yield similar to what occurred in other investigations [42]. However, some authors did not obtain differentiated production between their treatments fertilized only with organic amendments and the absence of fertilization [50].

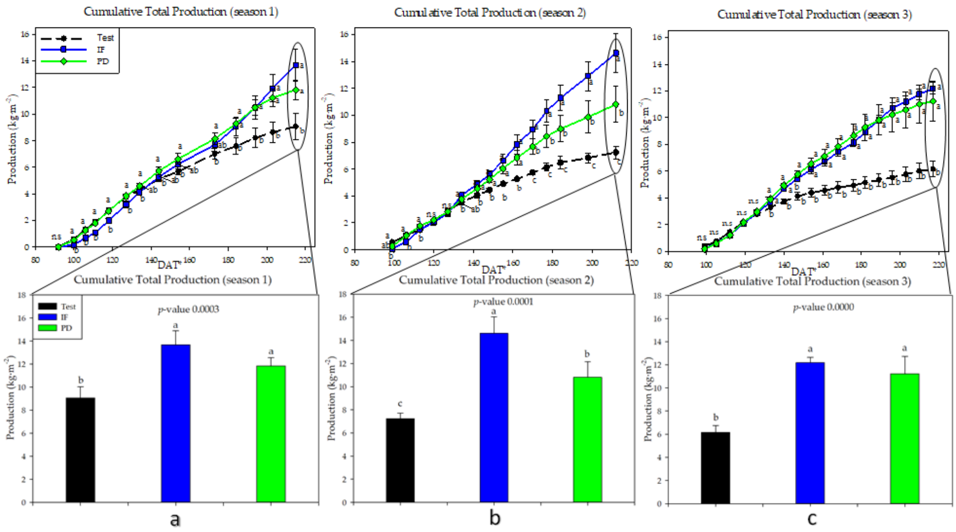

Figure 1. Cumulative tomato production in the three years of study (September–April cycles) as a function of crop nutrition: **(a)** Crop 1; **(b)**: Crop 2; **(c)**: Crop 3. Inorganic fertilization (IF); tomato plant debris (PD); no fertilization (test). Values (mean ± standard deviation). Different letters indicate significant differences ($p \leq 0.05$, Tukey's HDS test). DAT: days after transplanting.

In our trial, the study of the bacterial, fungal, and culturable fusarium microbiota showed a depressive effect after applying solarization. At the end of each campaign this microbial fraction was able to reestablish itself while becoming more evident in the experimental plots where tomato plant debris were added, which showed higher values than in the other treatments (Figure 2). Other investigations that have evaluated the depressive effect of greenhouse solarization on the microbiota of the arable soil have reported this capacity of the microbial population to recover at the end of the production cycle [51][52][53], although in some, there was no repetition of the solarization technique over time [51]. On the other hand, the classical biodiversity parameters of the fungal community were similar among the fertilization plans applied. However, repeated solarization caused a decrease in the values obtained, which has also been observed in the research conducted by Marín-Guirao *et al*. [51]. Our research suggests that the addition of tomato plant debris may have modified the composition of the filamentous fungi fraction during the first two years of the trial. Accordingly, other investigations have observed a change in the fungal community composition of a maize crop by incorporating straw versus the conventional crop [54]. The total number of fungal genera isolated from the greenhouse soil, considering all treatments and samplings, was 19, those being *Acremonium* spp., *Alternaria* spp., *Aspergillus* spp., *Cladosporium* spp., *Fusarium* spp., *Penicillium* spp., and *Rhizopus* spp. the most frequently isolated. This is similar to the findings of other studies that have used the technique of successive dilutions to study the fungal microbiota associated with horticultural greenhouses [24][51][52] and rainfed almond soil [41]. In the analyses for the genus *Fusarium there were* four different species isolated, the most abundant being *F. oxysporum*. Some experiments carried out in greenhouse cultivation report this species as the most abundant in the analyses performed after the end of cultivation, with *F. solani* being the most dominant after applying soil disinfection [53]. Likewise, a dominance of *F. oxysporum* has also been observed in soils where asparagus is grown outdoors, although the expression of these species is not homogeneous in all asparagus fields where the dominance of *F. equiseti* also stands out [55]. Thus, various functionalities are attributed to the isolated fungal microbiota, although in this research an independent study was not carried out to verify them. Different studies have observed the ability of fungal organisms to solubilize phosphorus (*Alternaria* spp., *Aspergillus* spp., *Penicillium* spp., *Trichoderma* spp., *Rhizopus* spp.) [56][57][58], participate in nitrification processes (*Aspergillus* spp., *Penicillium* spp.) [59], promote plant growth (*Trichoderma* spp.) [60] or practice saprophytism (*Aspergillus* spp., *Penicillium* spp., *Trichoderma* spp.) [61][62]. However, these effects are usually not fully clarified when considering the soil environment as a whole where multiple factors can condition the behavior of these microorganisms so that the simple modification of one of these conditions can determine the microoganisms present in the soil [60].

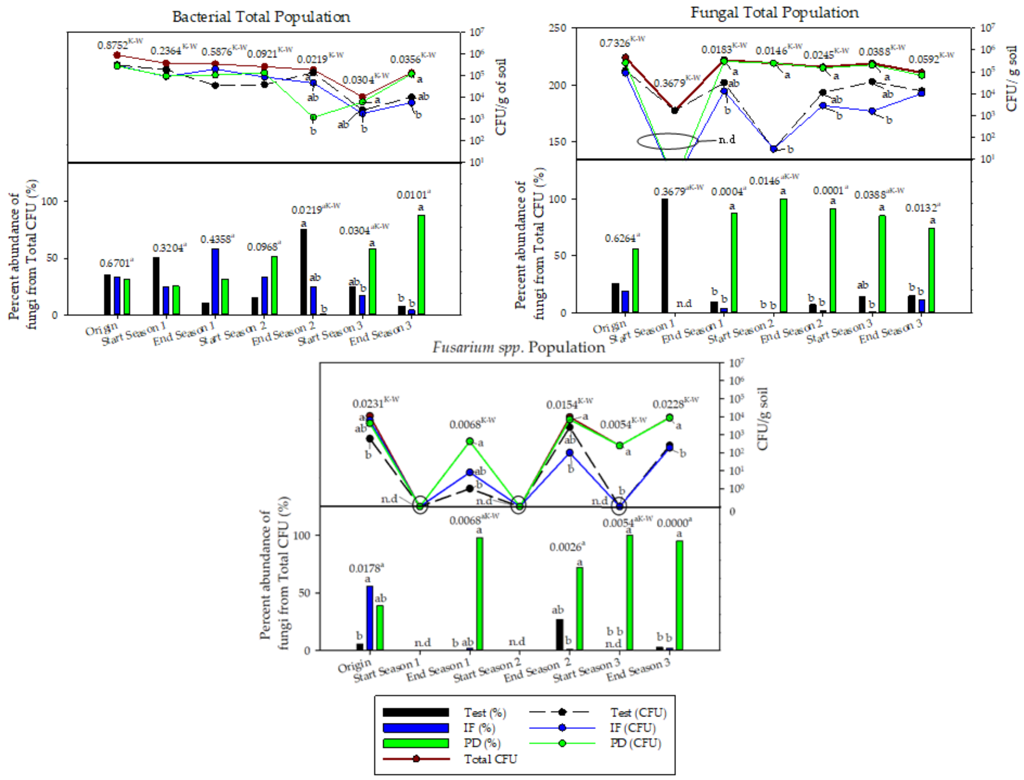

Figure 2. Soil microbiota in the three years of study (September–April cycles) as a function of crop nutrition. Inorganic fertilization (IF; n = 4); tomato plant debris (PD; n = 4); no fertilization (Test; n = 4). N.d: non detected. Values (average). Different letters above the bars and in the evolution lines indicate significant differences. ($p \leq 0.05$, Tukey's HDS test; $^{K\text{-}W}$: Kruskal–Wallis test).

In turn, the results of this research suggest that the addition of tomato plant debris with solarization increased the total nitrogen and assimilable potassium content. Mauromicale *et al*. [30][31] and Nuñez-Zofio *et al*. [29] observed an increase in these soil variables after applying their solarization protocols with organic amendments, while Seo *et al*. [49] only reported an increase in nitrate content. These authors observed an increase in assimilable phosphorus and soil electrical conductivity, something that did not occur in our trial possibly due to the difference in origin and nutrient composition of the organic amendments used. Likewise, the results suggest that the organic matter content of the soil did not increase significantly with the addition of tomato plant debris for three consecutive years. Other authors who have used solarization with different organic amendments did observe a significant increase in this soil variable throughout their experiments [24][29][63]. Thus, the higher content of some nutrients could have helped to maintain the final production of the plots that received tomato plant debris at levels similar to those obtained in the plots with inorganic mulch fertigation. The results suggest an improvement in soil hydraulic conductivity in the plots where solarization with tomato plant debris was applied. Biosolarization is a technique capable of modifying the soil infiltration rate as a consequence of the incorporation of organic amendments and their impact on soil structure [28]. This modification of soil hydraulic conductivity could have direct implications on the dynamics of irrigation applied to tomato crops (frequency and allocation), thus improving the water footprint of this production system compared to conventional fertilization.

The addition of tomato plant debris through solarization improved the vigor variables of the seedlings grown in a controlled environment chamber, mainly their leaf area and the dry weight of the aerial part, which are the parameters that best determine the vigor of the seedlings. The results obtained in this model support the findings obtained under greenhouse conditions. Thus, the leaf area of the different treatments increased after the application of solarization indistinct of the addition of tomato plant debris. Marín-Guirao *et al*. [24] obtained an increase in the vigor of their seedlings after applying a solarization protocol with organic amendments in a greenhouse where a commercial cucumber crop was grown. Similarly, the addition of organic amendments in a rainfed almond crop increased the vigor variables of cucumber seedlings compared to the conventional crop [41][64]. Our experimentation illustrates a low correlation obtained between the physicochemical variables of the soil and the vigor of cucumber seedlings, especially in the case of C/N ratio being the soil variable with the highest interdependence. Other studies have obtained a high correlation between soil productivity and physical, chemical, and microbiological variables, even postulating SOM as the most relevant variable in soil fertility, which in turn had a high correlation with fungal density and diversity. All of this is applicable when considering greenhouse soil with cucumber or tomato monocultures that showed a great disparity in their SOM content [25]. Although no relationships were found, the soil microbiota could have influenced these results. In our trial, a decreasing evolution of leaf area was observed in the treatment that only received inorganic fertilizers. Usero *et al*. [65] observed a negative influence on root dry weight, aerial dry weight and leaf area of tomato seedlings grown in pots under greenhouse that had been treated with an inoculum prepared from the microbiota present in the soil of a commercial greenhouse fertilized only with synthetic inorganic fertilizers versus others fertilized with organic amendments and a treatment without inoculation. This model with seedlings grown in a controlled conditions chamber allowed us to explain the possible influence of tomato plant debris on soil fertility, expressed by its vigor. This relationship could not be established with the physicochemical analyses performed on the soils studied (test, IF and PD). Their analytical performance remained constant in several of the parameters measured or did not show a clear difference, a behavior similar to that observed in other studies [24][25][41]. The suggested improvement in soil fertility observed through the leaf area of the seedlings could have influenced in keeping the yield of the tomato crop fertilized with only tomato plant remains from the previous crop similar to that offered by the conventional crop with inorganic fertilization.

3. Conclusions

The repeated reuse of tomato plant debris obtained at the end of the crop cycle as an organic amendment has a positive effect on the physical, chemical, and biological parameters that determine the fertility of greenhouse soil. Thus, by incorporating this material into the soil, the needs of the tomato crop are satisfied in cycles with a duration of approximately 215 DDT in reaching yields equal to those obtained by means of exclusive fertilization with conventional inorganic synthesis fertilizers while also maintaining the organoleptic quality of the fruit. The reuse by the producer of this vegetable by-product solves the problems linked to the external management of the material and contributes to a reduction in production costs in intensive horticultural farms through a more sustainable agricultural practice in accordance with the principles of the circular economy. Future studies should focus on the reuse of plant material from other horticultural species to determine its suitability for reuse as an organic amendment with benefits for crops and the sustainability of the greenhouse horticultural production process.

References

1. Baudoin, W.; Nersisyan, A.; Shamilov, A.; Hodder, A.; Gutierrez, D.; de Pascale, S.; Nicola, S.; Chairperson, V.; Gruda, N.; Urban, L. Good Agricultural Practices for Greenhouse Vegetable Production in the South East European Countries; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017; pp. 1–449. ISBN 978-92-5-109622-2.
2. European Comission. EIP-AGRI Focus Group Circular Horticulture: Final Report; EIP-AGRI Agriculture & Innovation: Brussels, Belgium, 2019; pp. 1–20.
3. de Andalucía, J. Cartografía de Invernaderos en Almería, Granada Y Málaga. Año 2020; Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible: Sevilla, España, 2020; pp. 1–24.
4. Duque-Acevedo, M.; Belmonte-Ureña, L.J.; Plaza-Úbeda, J.A.; Camacho-Ferre, F. The management of agricultural waste biomass in the framework of circular economy and bioeconomy: An opportunity for greenhouse agriculture in Southeast Spain. Agronomy 2020, 10, 489.
5. Camacho-Ferre, F. Técnicas de Producción de Cultivos Protegidos (Tomo II); Caja Rural Intermediterránea, Cajamar: Almería, España, 2004; pp. 389–776. ISBN 84-95531-16-X.
6. Cajamar. Análisis de la Campaña Hortofrutícola 2019/2020; Cajamar Caja Rural: Almerría, España, 2020; pp. 1–9.
7. Junta de Andalucía. Caracterización De Los Invernaderos De Andalucía; Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible: Sevilla, España, 2015; pp. 1–113.
8. Valera-Martínez, D.L.; Belmonte-Ureña, L.J.; Molina Aiz, F.D.; Camacho-Ferre, F. The greenhouses of Almería, Spain: Technological analysis and profitability. Acta Hortic. 2017, 1170, 219–226.
9. Vanthoor, B.H.E.; Stigter, J.D.; van Henten, E.J.; Stanghellini, C.; de Visser, P.H.B.; Hemming, S. A methodology for model-based greenhouse design: Part 5, greenhouse design optimisation for southern-Spanish and Dutch conditions. Biosyst. Eng. 2012, 111, 350–368.
10. Castro, A.J.; López-Rodríguez, M.D.; Giagnocavo, C.; Giménez, M.; Céspedes, L.; La Calle, A.; Gallardo, M.; Pumares, P.; Cabello, J.; Rodríguez, E.; et al. Six Collective Challenges for Sustainability of Almería Greenhouse Horticulture. Int. J. Environ. Res. Public Health 2019, 16, 4097.
11. Caparrós-Martínez, J.; Rueda-López, N.; Milán-García, J.; de Valenciano, J. Public policies for sustainability and water security: The case of Almeria (Spain). Glob. Ecol. Conserv. 2020, 23, e01037.
12. European Union. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on Waste. Off. J. Eur. Union L Ser. 2018, 150, 109–140.

13. European Comission. A new Circular Economy Action Plan. In For a Cleaner and More Competitive Europe; COM/2020/98 final. 11.3.2020; Office of the European Union: Brussels, Belgium, 2020; pp. 1–19.

14. European Comission. The European Green Deal; COM(2019) 640 final. 11.12.2019; Office of the European Union: Brussels, Belgium, 2019; pp. 1–28.

15. European Comission. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment; COM(2018) 673 final. 11.10.2018; Office of the European Union: Brussels, Belgium, 2018; pp. 1–14.

16. European Comission. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System; COM(2020) 381 final. 20.5.2020; Office of the European Union: Brussels, Belgium, 2020; pp. 1–23.

17. Aznar-Sánchez, J.A.; Velasco-Muñoz, J.F.; García-Arca, D.; López-Felices, B. Identification of opportunities for applying the circular economy to intensive agriculture in Almería (South-East Spain). Agronomy 2020, 10, 1499.

18. de Andalucía, J. Líneas De Actuación En Materia De Gestión De Restos Vegetales En La Horticultura De ANDALUCÍA; Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible: Sevilla, España, 2016; pp. 1–45.

19. Camacho-Ferre, F. Diferentes alternativas para la gestión del residuo biomasa procedente de cultivos de invernadero. In Innovaciones Tecnológicas en Cultivos de Invernadero; Fernández-Rodríguez, E.J., Ed.; Ediciones Agrotécnicas: Madrid, España, 2004; pp. 211–238. ISBN 94-87480-52-7.

20. Castillo-Díaz, F.J.; Ruiz-Olmos, C.A.; Gómez-Tenorio, M.Á.; Tello-Marquina, J.C. Efecto de la biosolarización sobre la producción de tomate cultivado bajo invernadero en Almería. Parte I: Evaluación de diferentes restos vegetales. Agrícola Vergel 2021, 432, 103–112.

21. García-Raya, P.; Ruiz-Olmos, C.; Marín-Guirao, J.I.; Asensio-Grima, C.; Tello-Marquina, J.C.; de Cara-García, M. Greenhouse Soil Biosolarization with Tomato Plant Debris as a Unique Fertilizer for Tomato Crops Greenhouse Soil Biosolarization with Tomato Plant Debris as a Unique Fertilizer for Tomato Crops. Int. J. Environ. Res. Public Health 2019, 16, 279.

22. Salinas, J.; Meca, D.; del Moral, F. Short-term effects of changing soil management practices on soil quality indicators and crop yields in greenhouses. Agronomy 2020, 10, 582.

23. Contreras, J.I.; Baeza, R.; Segura, M.L. Cuantificación de los nutrientes aportados al suelo por la incorporación de los restos de los cultivos hortícolas de invernadero. XI Congr. SEAE Agric. Ecológica Fam 2014, 1, 18–19.

24. Marín-Guirao, J.I.; Tello-Marquina, J.C. Microbiota edáfica y fatiga de suelo en invernaderos de la provincia de Gran. In I Jornadas de Transferencia Hortofrutícola de CIAMBITAL; Camacho-Ferre, F., Valera-Martínez, D.L., Belmonte-Ureña, L., Herrero-Sánchez, C., Reca-Cardeña, J., Marín-Membrive, P., del Pino-Gracia, A., Casa-Fernández, M., Eds.; Universidad de Almería y CIAMBITAL: Almería, España, 2017; pp. 17–36. ISBN 978-84-16389-98-8.

25. Marín-Guirao, J.I.; de Cara-García, M.; Crisol-Martínez, E.; Gómez-Tenorio, M.A.; García-Raya, P.; Tello-Marquina, J.C. Association of plant development to organic matter and fungal presence in Association of plant development to organic matter and fungal presence in soils of horticultural crops. Ann. Appl. Biol. 2019, 1, 1–10.

26. Tiessen, H.; Cuevas, E.; Chacon, P. The role of soil organic matter in sustaining soil fertility. Nature 1994, 371, 783–785.

27. Hijbeek, R.; van Ittersum, M.K.; ten Berge, H.F.M.; Gort, G.; Spiegel, H.; Whitmore, A.P. Do organic inputs matter—A meta-analysis of additional yield effects for arable crops in Europe. Plant Soil 2017, 411, 293–303.

28. Fernández, P.; Lacasa, A.; Guirao, P.; Larregla, S. Effects of Biosolarization with fresh sheep manure on soil physical properties of pepper greenhouses in Campo de Cartagena. In Proceedings of the 6th Workshop on Agri-Food Research, Murcia, Spain, 8–9 May 2017; Artés-Hernández, F., Cos, J.E., Fernández-Hernández, J.A., Calatrava, J.A., Aguayo, E., Alarcón, J.J., Guitiérrez-Cortines, M.E., Eds.; Universidad Politécnica de Cartagena: Cartagena, España, 2018; pp. 97–100. ISBN 9788416325641.

29. Núñez-Zofio, M.; Larregla, S.; Garbisu, C. Repeated biodisinfection controls the incidence of Phytophthora root and crown rot of pepper while improving soil quality. Span. J. Agric. Res. 2012, 10, 794–805.

30. Mauromicale, G.; Lo Monaco, A.; Longo, A.M.G. Improved efficiency of soil solarization for growth and yield of greenhouse tomatoes. Agron. Sustain. Dev. 2010, 30, 753–761.

31. Mauromicale, G.; Longo, A.M.G.; Lo Monaco, A. The effect of organic supplementation of solarized soil on the quality of tomato fruit. Sci. Hortic. (Amsterdam) 2011, 129, 189–196.

32. Marín-Guirao, J.I.; Tello-Marquina, J.C.; Díaz, M.; Boix, A.; Ruiz-Olmos, C.A.; Camacho-Ferre, F. Effect of greenhouse soil bio-disinfection on soil nitrate content and tomato fruit yield and quality. Soil Res. 2016, 54, 200–206.

33. Katan, J.; Greenberger, A.; Alon, H.; Grinstein, A. Solar Heating by Polyethylene Mulching for the Control of Diseases caused by Soil-Borne Pathogens. Phytopathology 1976, 66, 683–688.

34. Kirkegaard, J.A.; Gardner, J.; Desmarcherlier, J.M.; Angus, J.F. Biofumigation Using Brassica species to Control Pest and Diseases in Horticulture and Agriculture. In Preceedings of 9th Australian Research Assembly on Brassicas; Wrather, N., Mailes, R.J., Eds.; Agricultural Research Institute: Waga Wagga, Australia, 1993; pp. 77–82.

35. Palmero, D.; de Cara-García, M.; Santos, M.; Tello-Marquina, J.C. Control of diseases from forma especiales of Fusarium oxysporum causing wilt in intensive horticultural crops. Res. Signpost 2011, 661, 209–228.

36. Guerrero, M.M.; Lacasa, C.M.; Martínez, V.; Martínez-Lluch, M.C.; Larregla, S.; Lacasa, A. Soil biosolarization for Verticillium dahliae and Rhizoctonia solani control in artichoke crops in southeastern Spain. Span. J. Agric. Res. 2019, 17, 1–11.

37. Ros, C.; Martínez, V.; Sánchez-Solana, F.; López-Marín, J.; Lacasa, C.M.; Guerrero, M.; Del Mar GUERRERO Díaz, M.; Lacasa, A. Combination of biosolarization and grafting to control Meloidogyne incognita in greenhouse pepper crops. Crop. Prot. 2018, 113, 33–39.

38. Gómez-Tenorio, M.A.; Lupión-Rodríguez, B.; Boix-Ruiz, A.; Ruiz-Olmos, C.; Marín-Guirao, J.I.; Tello-Marquina, J.C.; Camacho-Ferre, F.; De Cara-García, M. Meloidogyne-infested tomato crop residues are a suitable material for biodisinfestation to manage Meloidogyne sp. in greenhouses in Almería (south-east Spain). Acta Hortic. 2018, 1207, 217–221.

39. Pankhurst, C.E.; Lynch, J.M. The role of soil microbiology in sustainable intensive agriculture. Adv. Plant Pathol. 1995, 11, 229–247.

40. FAO. Keep Soil Alive, Protect Soil Biodiversity; Food and Agriculture Organization of the United Nations: Rome, Italy, 2021; pp. 1–29.

41. Gómez-Tenorio, M.Á.; Magdaleno-González, J.; Tello-Marquina, J.C. Evaluación e Implementación de Técnicas Regenerativas Para la Mejora de la Fertilidad en el Cultivo del Almendro en las Provincias de Almería y Granada; Portal TecnoAgrícola: Madrid, España, 2021; pp. 1–132. ISBN 978-84-17596-98-9.

42. Bilalis, D.; Krokida, M.; Roussis, I.; Papastylianou, P.; Travlos, I.; Cheimona, N.; Dede, A. Effects of organic and inorganic fertilization on yield and quality of processing tomato (Lycopersicon esculentum Mill). Folia Hortic. 2018, 30, 321–332.

43. Pieper, J.R.; Barrett, D.M. Effects of organic and conventional production systems on quality and nutritional parameters of processing tomatoes. J. Sci. Food Agric. 2009, 89, 177–194.

44. Guajardo-ríos, O.; Lozano-cavazos, C.J.; Valdez-Aguilar, L.A.; Benavides-mendoza, A.; Ibarra-jiménez, L.; Ascacio-Valdés, J.A.; Aguilar-gonzález, C.N. Animal-based organic nutrition can substitute inorganic fertigation in soilless-grown grape tomato. Acta Agric. Scand. Sect. B Soil Plant Sci. 2018, 68, 77–85.

45. Polat, E.; Demir, H.; Erler, F. Yield and quality criteria in organically and conventionally grown tomatoes in Turkey e convencional na Turquia. Sci. Agric. 2010, 67, 424–429.

46. Martín-Expósito, E.; Marín-Guirao, J.I.; García-García, M.C.; de Cara-García, M. ¿Es suficiente un único abonado de fondo con estiércol en un cultivo de tomate ecológico bajo invernadero? In Proceedings of the VIII International Congress on Agroecology, Vigo, Spain, 2–3 July 2020; p. 686.

47. Gómez-Tenorio, M.A.; Ruiz-Olmos, C.A.; Marín-Guirao, J.I.; Martín, F.; Camacho-Ferre, F.; Tello-Marquina, J.C. La biodesinfección de un suelo arenado y relación con el lixiviado de nitratos. Acta Hortic. 2016, 327, 16–21.

48. Guerrero, M.M.; Ros, C.; Lacasa, C.M.; Martínez, V.; Lacasa, A.; Fernández, P.; Núñez-Zofío, M.; Larreglac, S.; Martíneza, M.A.; Díez-Rojo, M.A.; et al. Effect of biosolarization using pellets of brassica carinata on soil-borne pathogens in protected pepper crops. Acta Hortic. 2010, 883, 337–344.

49. Seo, M.W.; Lee, S.W.; Lee, S.H.; Jang, I.B.; Heo, H.J. Effect of Green Manure Incorporation and Solarization on Root Rot Disease of 3-year-old Ginseng in Soil of Continuous Cropping Ginseng. Korean J. Med. Crop. Sci. 2019, 27, 284–291.

50. Ruiz-Olmos, C.A.; Gómez-Tenorio, M.Á.; Camacho-ferre, F.; Belmonte-Ureña, L.J.; Tello-Marquina, J.C. Control de nematodos del género Meloidogyne en un suelo de invernadero cultivado con papaya utilizando la técnica de biosolarización de suelos. Terralia 2018, 116, 53–62.

51. Marín-Guirao, J.I.; de Cara-García, M.; Tello-Marquina, J.C. Effect of soil biodisinfection on soil fungal communities associated to horticultural crops. Ecosistemas 2019, 28, 63–72.

52. Martínez-Francés, M.A.; Lacasa-Plasencia, A.; Tello-Marquina, J.C. Ecología de la Microbiota Fúngica de los Suelos de los Invernaderos de Pimiento y su Interés Agronómico; Ministerio: Madrid, España, 2009; Volume 148, ISBN 9788449109874.

53. Martínez, M.A.; Martínez, M.C.; Bielza, P.; Tello-Marquina, J.C.; Lacasa-Plasencia, A. Effect of biofumigation with manure amendments and repeated biosolarization on Fusarium densities in pepper crops. J. Ind. Microbiol. Biotechnol. 2011, 38, 3–11.

54. Zhang, M.; Zhao, G.; Li, Y.; Wang, Q.; Dang, P.; Qin, X.; Zou, Y.; Chen, Y.; Siddique, K.H.M. Straw incorporation with ridge–furrow plastic film mulch alters soil fungal community and increases maize yield in a semiarid region of China. Appl. Soil Ecol. 2021, 167, 104038.

55. Brizuela, A.M.; De la Lastra, E.; Marín-Guirao, J.I.; Gálvez, L.; De Cara-García, M.; Capote, N.; Palmero, D. Fusarium Consortium Populations Associated with Asparagus Crop in Spain and Their Role on Field Decline Syndrome. J. Fungi 2020, 6, 336.

56. Mendes, G.D.O.; Luiz, A.; Freitas, M. De Mechanisms of phosphate solubilization by fungal isolates when exposed to different P sources. Ann. Microbiol. 2014, 64, 239–249.

57. López, J.E.; Gallego, J.L.; Vargas-ruiz, A.; Peña-mosquera, A.L.; Zapata-zapata, A.D.; López-sánchez, I.J.; Botero-botero, L.R. Aspergillus tubingensis and Talaromyces islandicus Solubilize Rock Phosphate Under Saline and Fungicide Stress and Improve Zea mays Growth and Phosphorus Nutrition. J. Soil Sci. Plant Nutr. 2020, 3, 2490–2501.

58. Ceci, A.; Pinzari, F.; Russo, F.; Maggi, O. Saprotrophic soil fungi to improve phosphorus solubilisation and release: In vitro abilities of several species. Ambio 2018, 47, 30–40.

59. Hora, T.S.; Iyengar, M.R.S. Nitrification by soil fungi. Arch. Mikrobiol. 1960, 35, 252–257.

60. Marín-guirao, J.I.; Rodríguez-Romera, B.; Lupión-Rodriguez, B.; Camacho-Ferre, F.; Tello-Marquina, J.C. Effect of Trichoderma on horticultural seedlings growth promotion depending on inoculum and substrate type Effect of Trichoderma on horticultural seedlings growth promotion depending on inoculum and substrate type. J. Appl. Microbiol. 2016, 121, 1095–1102.

61. Vassileva, M.; Malus, E.; Eichler-löbermann, B.; Vassilev, N. Aspegillus terreus: From Soil to Industry and Back. Microorganisms 2020, 8, 1655.

62. Sahu, A.; Manna, M.C.; Bhattacharjya, S.; Thakur, J.K.; Mandal, A.; Mahmudur, M.; Singh, U.B.; Bhargav, V.K.; Srivastava, S.; Patra, A.K.; et al. Thermophilic ligno-cellulolytic fungi: The future of e ffi cient and rapid bio-waste management. J. Environ. Manag. 2019, 244, 144–153.

63. Medina, J.J.; Miranda, L.; Soria, C.; Palencia, P. Non-Chemical Alternatives to Methyl Bromide for Strawberry: Biosolarization as Case-Study in Huelva (Spain). Acta Hortic. 2009, 842, 961–964.

64. Gómez-Tenorio, M.Á.; Magdaleno-González, J.; Castillo-Díaz, F.J.; Tello-Marquina, J.C. Influence of sheep manure on soil microbiota and the vigor of cucumber seedlings in soils cultivated with almond trees. Mod. Environ. Sci. Eng. 2021, accepted.

65. Usero, F.M.; Ármas, C.; Morillo, J.; Gallardo, M.; Thompson, R.B.; Pugnaire, F.I. Effects of soil microbial communities associated to different soil fertilization practices on tomato growth in intensive greenhouse agriculture. Appl. Soil Ecol. 2021, 162, 103896.