UNIVERSIDAD DE ALMERÍA

DEPARTAMENTO DE AGRONOMÍA

TESIS DOCTORAL

GESTIÓN RENTABLE Y SOSTENIBLE DE LOS RESIDUOS AGRÍCOLAS GENERADOS EN LA AGRICULTURA INTENSIVA DE ALMERÍA EN EL MARCO DE LA ECONOMÍA CIRCULAR

PROFITABLE AND SUSTAINABLE MANAGEMENT OF AGRICULTURAL WASTE GENERATED IN INTENSIVE AGRICULTURE IN ALMERIA IN THE FRAMEWORK OF THE CIRCULAR ECONOMY

Tesis por compendio de publicaciones para obtener el título de Doctor por la Universidad de Almería en el Programa de Doctorado en Agricultura Protegida

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ALMERÍA, ABRIL 2022

"Una síntesis vale por diez tesis"

Eugenio d'Ors

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TESIS POR COMPENDIO DE PUBLICACIONES

Esta Tesis Doctoral se defiende bajo la modalidad de compendio de publicaciones. Por ello, se encuentra formada por tres publicaciones de carácter científico que se encuentran incluidas en revistas de impacto indexadas en la base de datos JCR-SCI bajo los requerimientos que se establecen en la normativa de Estudios Oficiales de Doctorado para esta modalidad, aprobada en Consejo de Gobierno de la Universidad de Almería de 24 de febrero de 2017. Los manuscritos se publicaron con fecha posterior a la primera matriculación en el Programa de Doctorado de Agricultura Protegida y anterior a la fecha de depósito para la defensa de esta Tesis Doctoral.

A continuación, se indica la información referente a las publicaciones que forman parte de esta Tesis Doctoral:

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Título: The Management of Agriculture PlasticWaste in the Framework of Circular Economy. Case of the Almeria Greenhouse (Spain)

DOI: https://doi.org/10.3390/ijerph182212042

Nombre de la revista: International Journal of Environmental Research and Public Health (IJERPH). Special Issue Management of the Circular Economy in the Productive Sectors: Innovative Practices for a More Sustainable World

Volumen, número y páginas: 18(22), 12042

Año: 2021

Índice de impacto (2020): 3,390

Índice de impacto (5 años): 3,789

Categorías:

- Public, Environmental & Occupational Health (SSCI): Q1 (42/176)

- Public, Environmental & Occupational Health (SCIE): Q2 (68/203)
- Environmental Sciences (SCIE): Q2 (118/274)

ISSN: 1660-4601

Editorial: MDPI

País de publicación: Suiza

Revisión por pares: sí

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Título: Effect of Repeated Plant Debris Reutilization as Organic Amendment on Greenhouse Soil Fertility

Amendment on Greenhouse Soil Fertility

DOI: https://doi.org/10.3390/ijerph182111544

Nombre de la revista: International Journal of Environmental Research and Public Health (IJERPH). Special Issue Management of the Circular Economy in the Productive Sectors: Innovative Practices for a More Sustainable World

Volumen, número y páginas: 18(21), 11544

Año: 2021

Índice de impacto (2020): 3,390

Índice de impacto (5 años): 3,789

Categorías:

- Public, Environmental & Occupational Health (SSCI): Q1 (42/176)

- Public, Environmental & Occupational Health (SCIE): Q2 (68/203)
- Environmental Sciences (SCIE): Q2 (118/274)

ISSN: 1660-4601

Editorial: MDPI

País de publicación: Suiza

Revisión por pares: sí

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Título: Biodisinfection as a Profitable Fertilization Method for Horticultural Crops in the Framework of the Circular Economy

DOI: https://doi.org/10.3390/agronomy12020521

Nombre de la revista: Agronomy-Basel. Special Issue Circular Economy and Sustainable Development in Agriculture

Volumen, número y páginas: 12(2), 521

Año: 2022

Índice de impacto (2020): 3,417

Índice de impacto (5 años): 3,640

Categorías:

- Agronomy: Q1 (16/91)
- Plant Sciences: Q1 (57/235)

ISSN: 2073-4395

Editorial: MDPI

País de publicación: Suiza

Revisión por pares: sí

RESUMEN

En las últimas décadas, los ecosistemas han sufrido diversos impactos medioambientales a causa de las actividades antropogénicas, siendo la producción de alimentos una de ellas. Algunos de los impactos medioambientales de mayor importancia se originan a través de una aplicación excesiva de agroquímicos y una mala o nula gestión de los residuos obtenidos tras efectuar producción primaria. Para ello la Unión Europea ha desarrollado una política medioambiental acorde a la situación. Con ella se desea conseguir un modelo económico sostenible. La nueva actualización de esta política es *the Green Deal*. Con ella se pretende alcanzar un modelo económico estable disociado del consumo de recursos naturales y las emisiones de gases de efecto invernadero, fundamentado en la economía circular. En materia de agricultura se han establecido objetivos ambiciosos, destacándose un descenso del 50% en el uso y riesgo de los productos fitosanitarios o un descenso del 20% en el uso de fertilizantes a través de la estrategia *the Farm to Fork*. Además, deben aprovecharse todos los subproductos que se obtengan de los procesos productivos o aplicar un tratamiento de reciclaje adecuado en los casos que no puedan reutilizarse para minimizar su impacto medioambiental. En agricultura bajo abrigo se destaca la biomasa y plásticos agrícolas como los residuos de mayor importancia.

Por ello, la agricultura bajo invernadero de la provincia de Almería tiene un reto mayúsculo por delante, aún más si cabe cuando la mala gestión de residuos agrícolas es un mal endémico que arrastra desde su inicio. El objetivo planteado en esta Tesis Doctoral fue analizar el estado actual de las oportunidades disponibles para los distintos agentes implicados en la gestión de los residuos plásticos generados en el Modelo Almería en el marco de la economía circular y evaluar la adecuación que poseen diferentes enmiendas orgánicas (i.e., restos vegetales de la campaña anterior y *pellets* de *Brassica carinata*) para actuar como única fuente de nutrición de un modelo de cultivo circular de tomate.

Esta Tesis Doctoral se estructura en tres capítulos. En el primer capítulo se identifica el estado de la cuestión de los plásticos agrícolas en la agricultura bajo invernadero de Almería. Así, se está ocasionando un incremento en la producción de residuos y subproductos plásticos debido al incremento de superficie física de invernaderos que se ha registrado en los últimos años. El modelo de gestión actual no se adapta a las necesidades del sector, pues aún se originan vertidos plásticos a los espacios naturales. Sin embargo, se identifican diferentes oportunidades en el marco de la economía circular para mejorar. Además, se establece una relación entre el precio del barril de petróleo y la proporción de plásticos reciclados. Por se sugiere el interés de establecer algún tipo de bonificación para fomentar el uso de subproductos y reciclaje de plásticos.

En el segundo y tercer capítulo se analiza la viabilidad de sustituir los fertilizantes inorgánicos de síntesis por un modelo de producción circular abonado

solo con restos vegetales de tomate combinados o no con *pellets* de *Brassica carinata*, aplicando biosolarización en ciclos largos de tomate. Un ensayo de campo realizado durante tres años consecutivos.

El modelo de producción circular, a base reutilizar restos vegetales de tomate, obtuvo un rendimiento productivo y económico similar al cultivo convencional con fertilización inorgánica durante los ciclos de producción de tomate, mientras que la adición de con *pellets* de *Brassica carinata* redujo significativamente el beneficio económico del cultivo como consecuencia de incrementar los costes de producción.

La biosolarización redujo temporalmente la microbiota cultivable *ex* situdel suelo, pero esta se reponía al final del ciclo de producción a un nivel similar al identificado antes de aplicar el tratamiento de biodesinfección. Por otro lado, se observó una mejora de la fertilidad del suelo, lo que se tradujo en un descenso significativo de la dotación hídrica del modelo de producción circular frente al cultivo convencional.

Los resultados sugieren que utilizar un modelo de producción circular aprovechando la biomasa agrícola supone una oportunidad de interés para ayudar incrementar la sostenibilidad del Modelo Almería y ayudar a los productores a mitigar la estabilidad de los precios agrícolas debido al descenso de los costes de producción que se originan mediante la reutilización del subproducto vegetal.

Palabras clave: economía circular; gestión de residuos agrícolas; plástico, biomasa agrícola; desarrollo sostenible; cultivo alternativo

ABSTRACT

In recent decades, ecosystems have suffered various environmental impacts due to anthropogenic activities, food production being one of them. Some of the most important environmental impacts are caused by excessive application of agrochemicals and poor or non-existent management of waste from primary production. For this reason, the European Union has developed an environmental policy in accordance with the situation. The aim is to achieve a sustainable economic model. The new update of this policy is the Green Deal. The aim is to achieve a stable economic model that is decoupled from the consumption of natural resources and greenhouse gas emissions and is based on the circular economy. Ambitious targets have been set for agriculture, including a 50% reduction in the use and risk of phytosanitary products and a 20% reduction in the use of fertilizers through the Farm to Fork strategy. In addition, all by-products obtained from production processes should be used or appropriate recycling treatment should be applied in cases where they cannot be reused to minimize their environmental impact. In agriculture under shelter, biomass and agricultural plastics are highlighted as the most important residues.

Therefore, greenhouse agriculture in the province of Almeria has a major challenge ahead, even more so when the poor management of agricultural waste is an endemic problem that has been dragging along since its inception. The objective of this Doctoral Thesis was to analyze the current state of the opportunities available to the different agents involved in the management of plastic waste generated in the Almeria Model within the framework of the circular economy and to evaluate the suitability of different organic amendments (i.e., plant debris from the previous season and *Brassica carinata* pellets) to act as the sole source of nutrition for a circular tomato crop model.

This Doctoral Thesis is structured in three chapters. The first chapter identifies the state of the art of agricultural plastics in greenhouse agriculture in Almeria. Thus, there is an increase in the production of plastic waste and by-products due to the increase in the physical area of greenhouses that has been registered in recent years. The current management model is not adapted to the needs of the sector, as plastic waste is still being dumped in natural areas. However, different opportunities for improvement are identified within the framework of the circular economy. In addition, a relationship is established between the price of a barrel of oil and the proportion of recycled plastics. Therefore, the interest of establishing some kind of bonus to encourage the use of by-products and recycling of plastics is suggested.

The second and third chapters analyze the feasibility of substituting inorganic synthetic fertilizers with a circular production model fertilized only with tomato plant debris combined or not with Brassica carinata pellets, applying biosolarization in long tomato cycles. A field trial carried out during three consecutive years.

The circular production model, based on the reuse of tomato plant debris, obtained a similar productive and economic yield to conventional cultivation with inorganic fertilization during the tomato production cycles, while the addition of *Brassica carinata* pellets significantly reduced the economic benefit of the crop as a result of increased production costs.

Biosolarization temporarily reduced the *ex situ* culturable soil microbiota, but this was replenished at the end of the production cycle to a level similar to that identified before the biodisinfection treatment was applied. On the other hand, an improvement in soil fertility was observed, which resulted in a significant decrease in the water endowment of the circular production model compared to conventional cultivation.

The results suggest that using a circular production model taking advantage of agricultural biomass represents an opportunity of interest to help increase the sustainability of the Almeria Model and help producers mitigate the stability of agricultural prices due to the decrease in production costs caused by the reuse of the vegetable by-product.

Keywords: circular economy; agricultural waste management; plastics, agricultural biomass; sustainable development; alternative crops

INTRODUCCIÓN

1. Introducción

1.1. Unidad temática

1.1.1. La producción de alimentos y su efecto sobre los ecosistemas

Los ecosistemas han sufrido diversos impactos medioambientes a causa de las actividades antropogénicas. Así, se ha visto comprometida la calidad de las masas de agua, los suelos y la fauna y flora que los habita [1–5].

Precisamente, la producción de alimentos es una de las acciones generadoras de impactos [2,6–9]. En los últimos cincuenta años se ha triplicado el consumo de recursos naturales para producir los alimentos y fibras demandados por el ser humano [10]. Esto se originó a partir de la tercera Revolución Agrícola que implicó un cambio del modelo de producción que se practicaba hasta entonces. La demanda de alimentos generada por una población en continua expansión llevó a introducir nuevas variedades de cultivos básicos para la alimentación (i.e. arroz, maíz, trigo, etc.), nuevos insumos, principalmente agroquímicos; nuevas técnicas de producción y mayores necesidades de mecanización [11,12]. En este sentido, se transformaron los sistemas agrícolas en unas estructuras inestables con una alta dependencia de energía y generadora de una elevada cantidad de residuos.

De esta forma, los impactos generados por la actividad agrícola sobre los ecosistemas son diversos, pero destacan los fenómenos de erosión [13,14], la pérdida de diversidad genética [15], la degradación de los suelos [13,14] y la sobreexplotación y pérdida de calidad de las masas de agua [2]. Algunos de estos impactos medioambientales se originan por un consumo excesivo de agroquímicos (i.e. fertilizantes y fitosanitarios) y una mala o nula gestión de los residuos obtenidos tras realizar las actividades agrícolas [6,16,17].

1.1.2. La sostenibilidad medioambiental: Bioeconomía Circular

Los impactos medioambientales derivados de las actividades agropecuarias son contrarias a los principios de "Desarrollo Sostenible" formulados por la ONU en la declaración de Rio de Janeiro de 1992 [18]. Así, el "Desarrollo Sostenible o Duradero" se define como aquel "*que satisface la necesidades de la generación presente sin comprometer la capacidad de las generaciones futuras para satisfacer sus propias necesidades*" [19] (página 59). La definición menciona dos aspectos de importancia capital, las necesidades de las generaciones humanas y la capacidad limitada que muestra el medio ambiente para ofrecer bienes. Un sistema agrícola sustentable debería satisfacer los requerimientos de un ser humano a través de un uso racional de los recursos naturales, ajustándose a la capacidad de regeneración natural de estos [18,19], además de aplicar un adecuado tratamiento de gestión a los residuos generados [6,20].

Los Estados miembros de la ONU aprobaron la Agenda 2030 en septiembre de 2015 [21]. Esta se encuentra compuesta por 17 Objetivos de Desarrollo Sostenible (ODS) y 169 subobjetivos que tratan los aspectos sociales, económicos y medioambientales de mayor importancia a escala mundial, entre ellos la sostenibilidad de los sistemas agrícolas. Los documentos han afectado a las políticas realizada por la Unión Europea y España.

La modificación reciente de la política medioambiental europea se conoce como el *Pacto Verde Europeo* [22]. Este es el eje central de sus nuevas estrategias y normativas y se encuentra fundamentado en los principios de la economía circular y bioeconomía [23–26]. Estas disciplinas se definen como "*el mantenimiento del valor de los productos, materiales y recursos en la economía durante el mayor tiempo posible y la minimización de los residuos*" [27] (página 28) y "*la producción basada en el conocimiento y la utilización de recursos, procesos y métodos biológicos para proporcionar bienes y servicios de forma sostenible en todos los sectores económicos*" [28], respectivamente. Actualmente, se ha producido una sinergia entre ambos concentos, dando lugar a la bioeconomía circular. Este término recoge las características comunes de la economía circular y bioeconomía tales como pueden ser la reducción de la huella de carbono, uso de combustibles alternativos, uso de la biomasa o la valorización de los residuos. Se aplica a todos aquellos sectores cuya actividad económica tenga una base biológica pero que a su vez apliquen los principios de la circularidad [29]. Estos modelos de producción pretenden brindar una sostenibilidad social, económica y medioambiental de las estructuras de producción mientras se mantiene el desarrollo económico y la generación de empleo [22]. Con ello se pretende instaurar un modelo económico resiliente y no lineal, lo que supone un reto mayúsculo para todos los sectores de producción, incluida la agricultura.

En materia de agricultura se observa una influencia elevada de la estrategias *de la Granja a la Mesa* y la estrategia de *Biodiversidad* [30,31]. Se han marcado objetivos ambiciosos para alcanzar en 2050 un equilibrio en la emisión neta de gases de efecto invernadero y un crecimiento económico desligado del consumo de recursos [22]. En esta primera etapa se pretende reducir un 50% el uso y riesgo de los productos fitosanitarios, un 20% en la aplicación de fertilizantes, un 50% la pérdida de nutrientes, principalmente nitrógeno y fósforo; e incrementar la superficie ecológica hasta el 25% de las tierras agrícolas para el año 2030 [30]. Además, de preservar la biodiversidad de los ecosistemas [31]. Los organismos vivos que lo habitan desempeñan una labor de relevancia para mantener la multifuncionalidad y fertilidad de los ecosistemas [32], aportando el 50% del PIB mundial [31]. En estas estrategias se manifiesta la necesidad de emplear las técnicas y medios de producción que ofrezcan una mayor sostenibilidad a los sistemas agrícolas, además, de aprovechar los subproductos agrícolas y realizar una adecuada gestión de los residuos obtenidos tras realizar la producción de alimentos. En este sentido, se identifica la biomasa agrícola como un subproducto desaprovechado en la mayoría de los Estados miembros de la Unión Europea [23] y al plástico como uno de los mayores agentes contaminantes de los ecosistemas debido, principalmente, a su elevada capacidad de fragmentación y emisión de sustancias químicas como los bisfenoles [33–35].

1.1.3. Marco normativo de gestión de los plásticos y residuos vegetales: Aprovechamiento de subproductos

En la Figura 1 se muestran cinco de los diecisiete ODS de la Agenda 2030 que han servido como fundamento para algunas de las diferentes políticas, herramientas regulatorias, estrategias, planes de acción y comunicaciones que han realizado recientemente tanto la Unión Europea como sus Estados miembros con el objetivo de implementar en su sector productivo un desarrollo sostenible fundamentado en la economía circular, afectando, a los residuos generados en los distintos procesos, entre los que se encuentra la agricultura.

La Junta de Andalucía define a la basura plástica originada en la agricultura como los remanentes plásticos producidos tras efectuar la actividad agrícola, incluyendo a los recipientes de los productos fitosanitarios [36]. Precisamente, la clasificación de residuos de la Unión Europea excluye de entre los residuos plásticos no peligrosos a los envases obtenidos de las actividades agrarias y hortícolas [37] ante la contaminación que puede ir adherida por su contacto directo con agroquímicos, dándose consigo una subdivisión regulatoria entre estos restos [38,39]. En este sentido, los restos vegetales obtenidos tras realizar la actividad agrícola se engloban en la categoría de biomasa agrícola. Esta hace referencia a los residuos orgánicos obtenidos tras realizar la producción agrícola [40] y se encuentran incluidos en la clasificación de residuos no peligrosos de la Unión Europea [37].

La Directiva 2008/98/CE, de 19 de noviembre, modificada por la Directiva 2018/851, de 30 de mayo, estableció la obligación de elaborar planes de gestión para el tratamiento de los residuos obtenidos por los diferentes procedimientos productivos, a excepción de aquellos que no se encuentren dentro de su ámbito de aplicación por su especificidad o por la elaboración de bases jurídicas específicas para ellos (i.e., envases de agroquímicos). En ella también se remarcó que los residuos agrícolas no tienen la catalogación de residuo municipal por lo que su tratamiento deberá realizarse de manera independiente. Además, manifestó la necesidad de adoptar medidas que garanticen la reutilización de los elementos secundarios (subproductos). En este sentido, los plásticos agrícolas no peligrosos y la biomasa agrícola solo podrían catalogarse como subproductos, siempre que fueran obtenidos como un elemento secundario dentro de un proceso productivo, se garantice su reutilización, la transformación requerida sea la practicada normalmente por la industria y su uso final sea legal. [41,42]. La transposición al marco normativo nacional de la Directiva 2008/98/CE se realizó a través de la Ley 22/2011, de 28 de julio, siendo objeto de modificación por la Ley 5/2013, de 11 de junio [43,44], encontrándose en proceso de aprobación el contenido de la Directiva 2018/851, donde se le ha concedido un poder mayor a la economía circular bajo las directrices de la Unión Europea. En ellas, ha adoptado el contenido de la normativa marco de gestión de residuos y la clasificación europea de estos. Por otro lado, en el cuerpo normativo se fijó la posibilidad de establecer una responsabilidad ampliada al productor con el objetivo de alcanzar una mejor prevención, reutilización, reciclado y valorización de los residuos generados. Además, el nuevo texto legislativo contempla un impuesto al plástico no reutilizable con una base imponible de 0,45 € por cada kilogramo de plástico no reutilizable que se ponga en el mercado. Sin embargo, existen algunas exenciones entre las que se encuentran los plásticos de productos sanitarios y farmacológicos, los empleados para alimentos de uso médico y los plásticos empleados para los ensilados de uso agrícola y ganadero. Además, se reducen las trabas administrativas para las Comunidades Autónomas a la hora de autorizar el uso de subproductos dentro de su territorio [45].

La Directiva 94/62/CE del Parlamento Europeo y del Consejo, de 20 de diciembre de 1994, modificada por la Directiva (UE) 2018/852 del Parlamento Europeo y del Consejo de 30 de mayo de 2018 ordenó que todos los envases usados y recogidos deberán de gestionarse mediante un sistema de devolución y/o recogida para una posterior reutilización o valorización, junto con el establecimiento de un régimen de responsabilidad ampliada del productor [46,47]. El Estado español, incorporó la Directiva 94/62/CE a su código normativo bajo la Ley 11/1997, de 24 de abril, y Real Decreto 782/1998, de 30 de abril [48,49], observando en solo tres años la ineficacia de la reglamentación para algunos de los envases comerciales o industriales, entre ellos los recipientes de los productos fitosanitarios. Por ello, mediante la Ley 14/2000, de 29 de diciembre, de medidas fiscales, administrativas y del orden social, se introdujo una base jurídica donde se suprimía la posibilidad de exención de la responsabilidad ampliada del productor de algunos envases peligrosos de naturaleza comercial o industrial, evitando así que toda la obligación de tratamiento cayese sobre el consumidor final [50]. Así pues, el Gobierno español incorporó un cuerpo normativo específico que trataba sobre la gestión de los envases de los productos fitosanitarios a través del Real Decreto 1416/2001, de 14 de diciembre, en el cual se obligaba a los productores a establecer un sistema de depósito, devolución y retorno o alternativamente un sistema integrado de gestión de residuos de envases, donde éstos podrían indexarse voluntariamente, cuyo coste se deberá incorporar al precio de venta del producto [51].

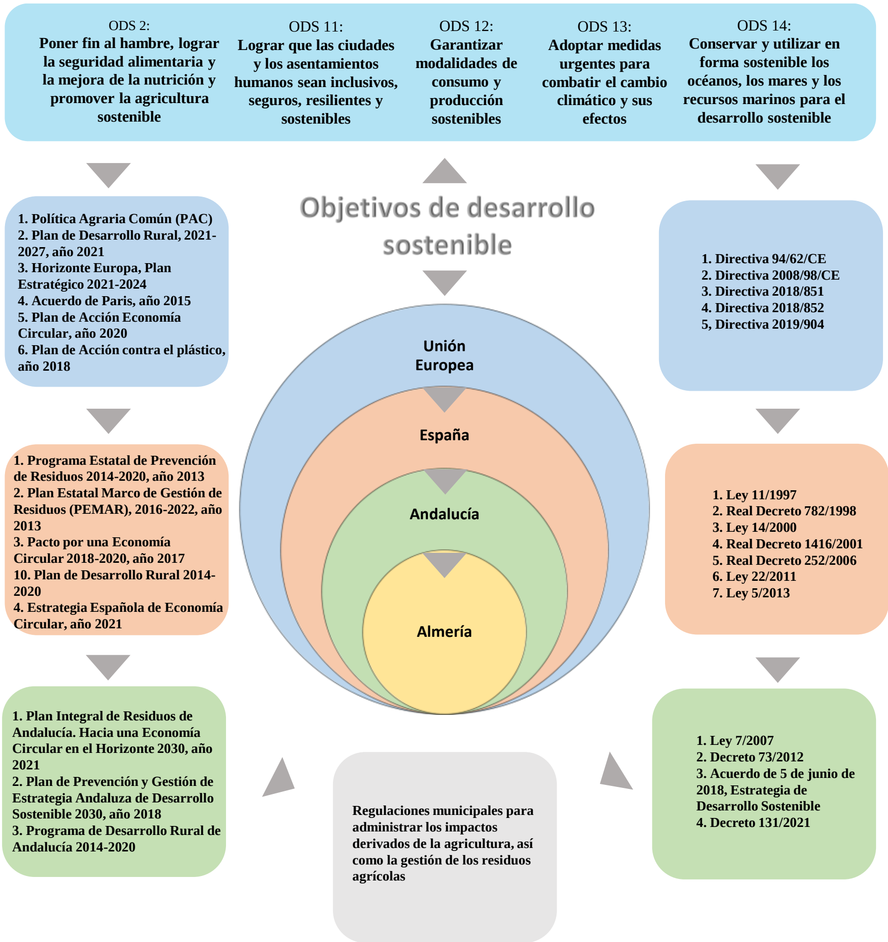

Figura 1. Políticas, marco legal, estrategias y planes de acción llevadas a cabo por la Unión Europea, España y Andalucía involucradas en la gestión de los subproductos/residuos plásticos agrícolas. Fuente: elaboración propia basado en [6].

Estas bases jurídicas nacionales llevaron al el Ministerio de Agricultura, Pesca y Alimentación y Medio Ambiente a la formulación de un Plan Estatal de Gestión de Residuos (PEMAR), donde, por primera vez, la gestión de los restos obtenidos de la actividad agropecuaria se abordaba en un capítulo específico para dicho fin, en el cual se manifestó la necesidad de implementar un proceso circular en la gestión de dichos residuos [52] y a la definición de un protocolo oficial para la identificación de subproductos [53].

La Comunidad Autónoma de Andalucía incorporó bajo un amplio conjunto de Leyes, Decretos, Decretos-Ley y Órdenes todas estas directrices a su normativa autonómica [54–60], identificando en ella la importancia que supone la gestión de los residuos agropecuarios en su territorio, ante el carácter primario e industrial de muchas de sus actividades productivas. El Gobierno andaluz, además, amplió en su normativa regional de gestión de residuos no peligrosos la responsabilidad de gestión para todos los agentes que pusieran por primera vez los plásticos en el mercado [55]. Así pues, ante el cambio de paradigma propuesto por la Unión Europea, la Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible de la Comunidad Autónoma de Andalucía ha desarrollado recientemente un Plan Integral de Residuos fundamentado en la Economía Circular basado en los criterios manifestados por la Unión Europea en estos últimos años [61].

1.1.4. Del subdesarrollo a la vanguardia: Modelo Almería

El sistema bajo invernadero de la provincia de Almería es una referencia a escala mundial. Este se ha desarrollado en apenas sesenta años, dejando atrás el subdesarrollo económico que padecía la provincia de Almería a principios del S. XX [62]. No obstante, el crecimiento que ha experimentado no fue lineal, pues ha tenido que hacer frente a diversos problemas durante su desarrollo (e.g., "crisis del isofenfos metil", "crisis de los pepinos", "crisis de vertidos de residuos agrícolas", etc.) [16,63–65].

En 2021, la superficie física de invernaderos creció hasta las 32.827 ha [66] y obtuvo 2.295,5 millones de euros por la venta de 3.509.459 toneladas de productos hortofrutícolas [67]. En este sentido, la agricultura almeriense posee una elevada estabilidad socioeconómica. La actividad agrícola genera una gran riqueza para el territorio y ofrece cinco veces más empleo que la media española [62].

Por otro lado, en el Modelo Almería es común el uso de técnicas y medios de producción respetuosos con el medioambiente durante la producción de su mercancía. Se emplea como estructura de producción mayoritaria al invernadero de tipo "Raspa y Amagado" [68], lo que genera una menor huella energética que otros modelos de producción similares como el holandés [69], al no requerir de una corrección climática debido a la climatología de la provincia de Almería [70]. Asimismo, es habitual el uso de técnicas de control agroecológicas (i.e., control biológico, injerto, solarización o biosolarización) para la liminar la expresión de las enfermedades o plagas que pueden padecer los organismos vegetales [70,71] y de producir bajo diferentes tipos de normas de calidad (i.e, GLOBALG.A.P, ecológico, etc.) [68]. Además, el modelo de producción emplea cubiertas plásticas – donde además se aplica la técnica del encalado– que provocan una elevada reflexión de la radiación solar [72] y es un gran fijador de dióxido de carbono (CO_2) debido al cultivo de más de 40.000 hectáreas de especies hortofrutícolas cada año, ayudando a luchar contra el cambio climático. Sin embargo, también han generado impactos medioambientales sobre los ecosistemas almerienses. Principalmente se ha causado una degradación de la calidad de las aguas subterráneas, impactos visuales derivados de la actividad agrícola, una pérdida de biodiversidad o una acumulación de residuos en los espacios naturales [6,34,73–75].

La gestión de los residuos agrícolas del Modelo Almería: Un mal endémico

Los residuos agrícolas generados durante la producción hortofrutícola bajo invernadero de Almería han causado diferentes crisis sanitarias a lo largo de la vida del Modelo Almería [16,65,76]. Estas se han se han originado por verter residuos agrícolas en los espacios naturales almerienses, provocando su contaminación [34,65]. En este sentido, se han identificado contaminaciones sobre los suelos, agua y paisaje [6,34,65,75].

A principios del S. XXI se llevó a cabo la primera limpieza del campo agrícola almeriense. Esta se denominó como "barrido cero". Con ella se eliminaron todos los residuos hallados en las zonas agrícolas de Almería. La mayor parte de ellos eran residuos vegetales mezclados con las rafias de entutorado [65]. La situación se abordó, incluso, en el Parlamento de Andalucía. Y fue descrita por el Consejero de Agricultura y Pesca de la VI legislatura de la siguiente forma: "*De acuerdo con el sector y los Ayuntamientos de Poniente y Levante hemos invertido 1.000 millones de pesetas, aproximadamente, para la limpieza de todo el campo de Almería, el denominado barrido cero, cuyos resultados ustedes tuvieron ocasión de conocer y comprobar personalmente hace pocos días. A la finalización de esta operación, que se producirá en fechas próximas y que no tiene, por otra parte, precedente en nuestro país, pues, cuando se produzca esa finalización habremos retirado un total de 1.740.000 metros cúbicos de residuo*" (Junta de Andalucía, 2001, p.5712).

Tras la limpieza y la mejora del protocolo de tratamiento de los residuos agrícolas de la provincia de Almería la situación mejoró. Sin embargo, las limpiezas del campo son recurrentes. En 2018, la Junta de Andalucía invirtió seis millones de euros para limpiar los campos de Almería, Granada y Huelva, principalmente de residuos plásticos [16]. Por lo que parece que el actual sistema de gestión no de adapta a las necesidades del sector. La mayor problemática la origina los residuos plásticos y la biomasa agrícola [16,20,76].

La producción estacional es una de las principales características de la producción de los residuos agrícolas. Principalmente, se generan al finalizar los ciclos de producción. La elevada producción de residuos (1,8 millones de toneladas de restos vegetales y 90.738 toneladas de residuos inorgánicos) y su alta estacionalidad son las principales barreras en el tratamiento de los materiales [20,76]. En Almería, el 80% de los restos vegetales se generan en los meses de febrero, mayo y junio; mientras que el 80% de los residuos plásticos se generan en los meses de agosto y septiembre [73,76]. Esta situación dificulta el diseño de los protocolos de tratamiento industriales a causa de no disponer de unos aportes estables mensuales [77]. La falta de espacio es las explotaciones agrícolas, una logística de trasportes inadecuada, la contaminación cruzada entre residuos agrícolas (e.g., mezcla de restos vegetales y elementos plásticos) y la lejanía de las plantas de gestión son otros condicionantes que dificultan la gestión de los residuos agrícolas [76].

Bioeconomía y Economía Circular: oportunidad para el Modelo Almería

A la vista de los cambios normativos y estratégicos realizados por las Administraciones regionales, nacionales e internacionales y la problemática que suscita el tratamiento de los residuos en el Modelo Almería se observa la necesidad de implantar un entramado productivo basado en los principios de la economía circular y bioeconomía, aprovechando los subproductos obtenidos de la producción de la mercancía hortofrutícola. Precisamente, existen diferentes técnicas de cultivo y medios de producción que pueden ofrecer un mayor grado de sostenibilidad en la actividad agrícola (i.e., plásticos biodegradables, medidas administrativas, uso de biodesinfección del suelo, aprovechamiento de biomasa vegetal, etc.) y mejorar, además, la problemática ligada a la gestión de la biomasa y plásticos agrícolas [20,78,79].

1.2. Hipótesis y objetivos

1.2.1. Hipótesis

Esta Tesis Doctoral parte de la hipótesis de que en Modelo Almería se producen grandes cantidades de residuos y subproductos agrícolas que deben ser reciclados y reutilizados para mantener sostener la sostenibilidad del sistema agrícola. Así, basados en el marco de la economía circular, existirán diferentes oportunidades (i.e. productivas, económicas, medioambientales, etc.) para los productores del sistema agrícola bajo invernadero de la provincia de Almería que, a su vez, se pueden extrapolar para otras áreas invernadas de la agricultura española.

1.2.2. Objetivos

Objetivo general

El objetivo general que se planteó en esta Tesis Doctoral fue analizar el estado actual de las oportunidades disponibles para los distintos agentes implicados en la gestión de los residuos plásticos generados en el Modelo Almería bajo el marco de la economía circular y evaluar la adecuación que poseen diferentes enmiendas orgánicas (i.e., restos vegetales de la campaña anterior y *pellets* de *Brassica carinata*) para actuar como única fuente de nutrición en un modelo de cultivo de tomate basado en la economía circular.

Objetivos específicos

Objetivo 1: Estimar la producción y coste de gestión de los residuos y subproductos plásticos agrícolas, generados en el sistema productivo hortofrutícola bajo invernadero de la provincia de Almería, desde el punto de vista del sistema actual de gestión, oportunidades en su tratamiento y su relación con el coste de las materias primas bajo el marco de la economía circular.

Objetivo 2: Evaluar el efecto de un modelo de producción regido por los principios de la economía circular a través de reutilizar los restos vegetales de tomate de la campaña anterior mediante biosolarización actuando como única fuente de abonado frente a la fertilización inorgánica y la no fertilización sobre la producción final comercial, su calidad y variables físicas, químicas y biológicas del suelo durante tres ciclos únicos de tomate.

Objetivo 3: Evaluar el efecto de un modelo de producción regido por los principios de la economía circular a través de utilizar diferentes dosis de enmiendas orgánicas (i.e., restos vegetales de tomate y *pellets* de *Brassica carinata*) actuando como única fuente de abonado frente a la fertilización inorgánica y la no fertilización sobre la producción final comercial, su calidad, vigor vegetal de plantas crecidas en condiciones controladas y beneficio económico durante tres ciclos únicos de tomate.

1.3. Estructura del trabajo

A continuación, se realizará una descripción de la estructura del compendio de trabajos de esta Tesis Doctoral. Para ello se expondrá el contenido de mayor importancia de los materiales y métodos (realizándose una segmentación entre los ensayos de revisión y campo) y resultados de los diferentes trabajos.

1.3.1. Metodología

1.3.1.1. Análisis de revisión

Para estimar la producción de residuos y subproductos plásticos del Modelo Almería y explorar las oportunidades disponibles para los agricultores se siguió el procedimiento comunicado por Duque-Acevedo et al. [6]. Para ello se realizó una compilación, clasificación, comprobación y análisis detallado de la información obtenida de diversos estudios, informes técnicos, normativa y estadísticas de diferentes organismos públicos y privados con facultad y/o relación con la temática abordada, los cuales tuvieron desde una catalogación local hasta internacional. Además, se realizaron consultas telefónicas con los distintos departamentos de las instituciones públicas regionales y locales encargadas de la gestión de los datos de interés para validar la información recopilada de sus páginas web oficiales.

Por otro lado, se llevaron a cabo diferentes entrevistas telefónicas o por correo electrónico con distintos agentes que estaban relacionados con la producción, comercialización o gestión de los plásticos agrícolas, con el objetivo de ampliar y verificar la información hallada en bibliografía.

Influencia externa del coste de la materia prima en el aprovechamiento de los subproductos plásticos

Se evaluó la influencia del precio Brent del petróleo sobre la proporción de plástico reciclado en la Unión Europea y sus Estados miembros y la provincia de Almería. Para ello se calculó el precio Brent anual del barril de petróleo crudo (serie 1987-2020; $/barril) con un desfase mensual desde t-12 hasta t+12 a partir de los valores ofrecidos por la Administración de Información Energética (EIA) de EE. UU. Adicionalmente, se obtuvo la proporción de plástico "packing" reciclado por la Unión Europea y sus Estados miembros (UE-27) y el porcentaje de envases ligeros reciclados por la provincia de Almería (serie 1997-2018). Finalmente, se estableció una correlación entre ambas variables mediante el coeficiente de Pearson (r) con la prueba F, realizando la comprobación de las asunciones necesarias para su aplicación.

1.3.1.2. Ensayo de campo

Localización del ensayo

Los ensayos se efectuaron durante tres campañas consecutivas (2015/2016 a 2017/2018) en un invernadero situado en la Finca Experimental UAL-ANECOP. Su emplazamiento residía en el paraje de "Los Goterones", perteneciente a la localidad de Retamar del término municipal de Almería (España) (polígono 24; parcela 281).

Características del invernadero

El invernadero experimental era representativo dentro del Modelo de producción almeriense. Este tenía una estructura de tipo "Raspa y Amagao" [68,80], con una altura máxima y mínima de 4,70 y 3,40 m, respectivamente. La cubierta del invernadero era de polietileno transparente de 200 μm de espesor, con ventanas laterales y cenitales, que incluían una malla anti-trips. El invernadero tenía una superficie de 1.784 m^2 y una orientación de noroeste-suroeste, al igual que las líneas de cultivo.

Diseño experimental

En esta investigación se siguió un diseño experimental que consistió en dividir el área del invernadero en dos bloques claramente diferenciados entre sí, a través del pasillo central de hormigón de la estructura (zona 1 y 2) (Figura 2). Precisamente, la razón principal de este criterio de partición fue por la subdivisión existente en los sectores de riego del invernadero, con lo cual se permitió aplicar un manejo diferenciado de agua y fertilizantes inorgánicos en cada sector. En la zona 2, se ubicaron todos los tratamientos a los que se les suministro una fertilización inorgánica de cobertera, indistintamente de su combinación o no con enmiendas orgánicas, mientras que en la zona 1 se destinó para las parcelas experimentales que se abonaron únicamente con enmiendas orgánicas o que no se fertilizaron.

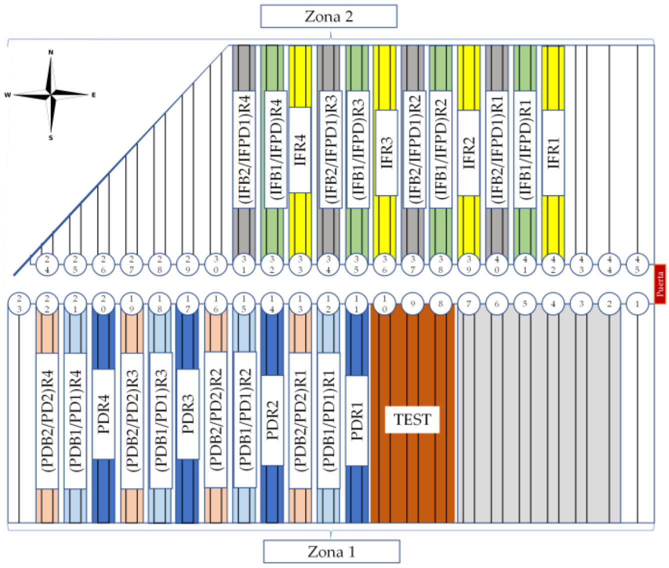

Figura 2. Distribución espacial de los tratamientos en la superficie del invernadero. Test: testigo sin fertilización; PD: restos vegetales de tomate del cultivo anterior; B: *pellets* de *Brassica carinata*; IF: fertilización inorgánica.

Los tratamientos empleados en los años de ensayo fueron los siguientes:

- Test: sin fertilización (años 1, 2 y 3)
- IF: fertilización inorgánica (años 1, 2 y 3)
- IFB1: fertilización inorgánica + 0,5 kg·m^{-2} de pellets de *Brassica carinata* (años 1 y 2)
- IFB2: fertilización inorgánica + 1,0 kg·m^{-2} de pellets de *Brassica carinata* (años 1 y 2)
- IFPD: fertilización inorgánica + 3,5 kg·m^{-2} de restos vegetales de tomate (año 3)
- IFPD1: fertilización inorgánica + 5 kg·m^{-2} de restos vegetales de tomate (año 3)
- PD: 3,5 kg·m^{-2} de restos vegetales de tomate (años 1, 2 y 3)
- PD1: 5 kg·m^{-2} de restos vegetales de tomate (año 3)
- PD2: 6,5 kg·m^{-2} de restos vegetales de tomate (año 3)

Proceso de biodesinfección.

En los tres años de ensayo, se realizó una biosolarización o solarización del suelo del invernadero previa al establecimiento del cultivo de tomate durante los meses de verano (Figura 3). El protocolo fue similar durante los tres años de ensayo. Este comenzaba con la eliminación de los restos vegetales crecidos en la nave durante la campaña anterior y su deposición en el pasillo central del invernadero. Tras esta operación se recogían los ramales porta-goteros y se despejaba la superficie del suelo de la nave.

Figura 3. Proceso de autogestión de los restos vegetales de tomate de la campaña anterior. A: restos vegetales frescos depositados sobre el pasillo de hormigón del invernadero; b: trituración de los restos vegetales; c: restos vegetales mezclados en el perfil superior del suelo; d: plástico de solarización.

Posteriormente, los restos vegetales de la campaña anterior se trituraban mediante una picadora de cadenas con el objetivo de obtener un tamaño de partícula adecuado que facilitase su descomposición (de aproximadamente 2 cm de longitud). Sin embargo, en el tercer año se requirió de una labor extra, que se realizó de manera previa al triturado de los restos vegetales, y fue la rotulación del terreno mediante el uso de un subsolador de 40 cm de profundidad. Esta labor se realizó en ambos sectores, pero tenía como objetivo el fragmentar la losa de marmolina hallada en el cuarto suroeste de la zona 2 del invernadero.

A continuación, se depositaron y uniformizaron las enmiendas orgánicas sobre el área destinada al tratamiento correspondiente a las dosis ensayadas. La incorporación de los *pellets* de *Brassica carinata* se realizó mediante carillas, de 20 m de largo, 0,4 m de ancho y 0,3 m de largo. Tras la deposición del material orgánico en el interior de las carillas, y el cierre de estas, se reinstalaban los ramales porta-goteros y se evaluaba la correcta emisión de agua por parte de los goteros ante la importancia de la humedad en el procedimiento de biosolarización.

A continuación, se tapó la superficie del suelo del invernadero con una cubierta plástica transparente (de polietileno) de 50 μm de espesor, eliminando cualquier bolsa de aire que pudiera formarse durante la instalación. Además, el perímetro de la cubierta plástica se sellaba a través de una zanja rectangular (con una base de 0,20 m y una profundidad de 0,30 m), las láminas de plástico se enlazaban entre sí mediante grapas, y entre las raspas y amagados del invernadero se efectuaba por medio de una cinta adhesiva. Tras finalizar todas las etapas, se aplicaba una dotación hídrica aproximada de 53,5 $L·m^{-2}·año^{-1}$ durante los cuatro días. La duración de los tratamientos de solarización o biosolarización era de tres meses, y en todos los años se realizó entre los meses de junio a septiembre.

Labores culturales realizadas durante el cultivo

- **Duración de los ciclos de producción**

En los tres años de investigación se realizaron tres ciclos únicos de producción. Estos comenzaron durante cada año a principios del mes de septiembre y finalizaron en la segunda semana de abril del mes siguiente. La duración fue de 215, 212 y 215 días después del trasplante (DDT) para el primer, segundo y tercer año de ensayo.

- **Trasplante**

Se emplearon plántulas de tomate (*Solanum lycopersicum* Mill.) de cinco semanas de edad que habían sido crecidas en un semillero comercial para el experimento a una densidad de plantación de 2 plantas/m^2. El tratamiento dado a las semillas, y posteriormente a la plántulas, fue análogo al llevado a cabo para las plantaciones comerciales.

La variedad comercial seleccionada fue un cultivar de tipo canario: "Pitenza F1" (Enza Zaden, Enkhuizen, Países Bajos).

- **Labores culturales realizadas tras el trasplante**

El manejo cultural realizado se ajustó a lo manifestado por Camacho-Ferre [81], consistiendo en las prácticas agronómicas que emplean los agricultores del modelo de producción almeriense para cultivo del tomate.

- **Recolección de los frutos**

La recolección de los frutos se realizó de manera manual y unitaria durante toda la investigación, comenzado cada año de ensayo durante el mes de diciembre y extendiéndose hasta el final de cada ciclo de producción, teniendo una periodicidad máxima de hasta dos semanas. El producto era destinado a tomate en suelo debido a los requerimientos de la entidad comercializadora.

- **Riegos y fertilización inorgánica**

A cada zona del invernadero (1 y 2) se le aplicó un volumen hídrico a demanda de acuerdo con las lecturas realizadas de dos tensiómetros que se encontraban distribuidos en el invernadero (a razón de uno por zona). El tensiómetro era de la marca y modelo IRROMETER Modelo R (Irrometer, Riverside CA, EE. UU.) y se encontraba instalado a 30 cm de profundidad.

Además, se aplicó una solución nutritiva inorgánica a los tratamientos ubicados en la zona 2, calculada bajo los principios de nutrición manifestados por Steiner (1961).

Variables analizadas

- **Producción comercial**

Las variables de producción se calcularon tras realizar la primera cosecha de cada año de ensayo y hasta el final de éstas. Los índices de destrío obtenidos durante cada año de ensayo fueron nulos, debido a la confección previa realizada en los ramilletes, la cual fue idéntica entre los tratamientos ensayados durante toda la investigación.

Para ello, se realizó la cuantificación independiente de los frutos obtenidos de cada parcela experimental mediante una balanza Metter Toledo® (Ohio, Estados Unidos) con una sensibilidad de 0,01 g. Antes de iniciar el proceso de medida de cada día de recolección se hallaba la masa de tres cajas plásticas, cuyo promedio era eliminado del valor absoluto de producción obtenido. Además, se cuantificaban el número de plantas total existente por parcela experimental para ajustar la producción obtenida a la densidad de plantación inicial. Por último, se calculaba la producción puntual y acumulada por unidad de superficie.

- **Calidad de los frutos**

La masa de los frutos se calculó a partir de la medida de 25 frutos seleccionados al azar durante cada una de las cosechas realizadas a lo largo de la investigación [83]. La medida se realizó en una balanza Metter Toledo® (Ohio, Estados Unidos) que poseía una sensibilidad de 0,01 g. Asimismo, para la medición se empleó siempre una caja plástica de masa conocida.

El diámetro ecuatorial de los frutos de tomate se midió mediante un calibre digital de sensibilidad 0,01 mm (Mitutoyo; Kanagawa, Japón); la firmeza de la pulpa se obtuvo a partir de un durómetro de sensibilidad 0,001 $kg \cdot cm^{-2}$ (Agrosta Penefel DFT14; Francia), la acidez de la pulpa del fruto se midió a través de un pH-metro de sensibilidad 0,01 unidades (Crison pH-25; Barcelona, España); y el contenido el sólidos solubles totales se obtuvo mediante un refractómetro de sensibilidad 0,1 °brix (Atago pal-1; Tokio, Japón). Estas variables se midieron en de 10 frutos seleccionados al azar para cada parcela experimental y día de análisis.

- **Análisis físicos, químicos, biológicos y de vigor vegetal**
    - **Muestreos y muestras de suelo**

Durante los experimentos se realizaron siete muestreos diferentes. El primero se llevó a cabo antes de aplicar los protocolos de biodesinfección. Los seis muestreos restantes se efectuaron tras finalizar la biodesinfección del suelo (primera semana de septiembre) y al finalizar el ciclo de producción (segunda semana de abril) de cada año de cultivo. Se realizaban dos muestreos por año.

- **Estudio de la microbiota bacteriana, fúngica y oomicetos**
  - **Preparación de las muestras de suelo**

Las muestras de suelo se procesaron siguiendo el protocolo indicado por Tello-Marquina *et al.* (1991). En primer lugar, se depositó 1 kg por muestra en una bandeja de polietileno donde se les dejó secar durante 7-10 días, hasta conseguir una muestra de masa constante. Posteriormente, se trituraron con un mortero de porcelana y se tamizaron con un tamiz de 200 μm de luz.

  - **Método analítico**

La microbiota cultivable de los suelos (bacterias y hongos) se estudió mediante el método de las diluciones sucesivas [84] en un medio de cultivo agar-malta acidificado, mientras que los hongos filamentosos del género *Fusarium* se evaluaron aplicando la recomendación de Warcup, empleándose para ello el medio de cultivo semi-selectivo de Komada modificado [84,85].

Tras el periodo de incubación se cuantificaron las Unidades Formadoras de Colonias (UFC) de ambos análisis. Los hongos filamentosos presentes en el estudio general (i.e, medio de cultivo agar-malta acidificado) se identificaron a escala de género a través de las claves taxonómicas de Barnet y Hunter [86] y Elis [87]. La microbiota fusárica aislada en los análisis semi-selectivos se identificaron a escala de especie mediante las claves taxonómicas de Nelson et al. [88] y Leslie y Summerell [89]. Tras expresar los resultados en UFC/g de suelo seco se calcularon diferentes variables descriptivas de la comunidad fúngica [90–93]

- **Estudio de la física y química del suelo**

La determinación de los parámetros físicos y químicos de las muestras de suelo se externalizó al Laboratorio Agroalimentario de Granada de la Consejería de Agricultura, Pesca y Desarrollo Rural de la Junta de Andalucía. Las evaluaciones se llevaron a cabo a través de los métodos estandarizados que se encuentran recogidos en la Orden 5/12/1975 (materia orgánica del suelo, nitrógeno total, fósforo Olsen, potasio asimilable, caliza activa, carbonatos, pH, conductividad eléctrica y textura) [94]. La conductividad hidráulica del suelo en saturación (K_h) se estimó a partir del modelo propuesto por Saxton y Rawls [95].

- **Evaluación del crecimiento de plántulas en una cámara de ambiente controlado**

Se llevó a cabo un experimento en macetas para evaluar cómo impactaban los suelos en el crecimiento de plantas hortícolas desarrollas en una cámara de ambiente controlado. Las especies hortícolas utilizadas fueron pepino (*Cucumis sativus cv.* Marketmore 76; Ramiro Arnedo S.A, Calahorra, Spain) y tomate

(*Solanum lycopersicum* L. *cv.* Río Grande; Ramiro Arnedo S.A., Calahorra, Spain.). Se empleó la metodología expuesta por Marín-Guirao *et al.* [96]. Por problemas de conservación de las muestras, las evaluaciones no se realizaron con los suelos muestreados al finalizar el cultivo en el tercer año de estudio.

Al finalizar los ensayos se evaluaron las cinco variables: número de hojas, altura de las plántulas, masa seca de la raíz, masa seca aérea y área foliar.

- **Análisis económico**

Se realizaron dos análisis económicos que se rigieron por el principio de maximizar el beneficio de los agricultores. Se realizó una propuesta de reducción de la cuenta de gastos mediante la autogestión de los restos vegetales y el descenso de diversos insumos agrícolas (i.e., agua, fertilizantes, desinfectantes químicos y manejo del enarenado) a raíz de su uso. Se empleó como parámetro determinante el beneficio antes de impuestos (NPbt) [97]. La variable fue calculada mediante la siguiente expresión matemática:

$$NPbt=TNR-TC, \qquad (1)$$

NPbt: beneficio antes de impuestos; TNR: ingresos anuales totales; TC: costes totales.

- **Análisis 1**

Se estudió el beneficio económico antes de impuestos con carácter anual obtenido por los 11 tratamientos aplicados en el invernadero experimental (Tabla 1).

- **Análisis 2**

Se evaluó el beneficio económico antes de impuestos de las cinco alternativas hortícolas sugeridas por Honoré et al. [97] extendiendo el periodo de análisis hasta enero de 2021. Se emplearon cinco rotaciones de cultivo que se usan de manera común en el Modelo Almería, compuestas por ocho especies vegetales (cuatro cucurbitáceas, tres solanáceas y una leguminosa) [62,70] (Tabla 1).

La duración estimada de la fase de desarrollo vegetativo y periodo productivo para cada campaña ha sido de 310 DDT. Se ha considerado destinar 55 días para las demás labores pre y post-cultivo. Las cinco alternativas hortícolas se sometieron a tres metodologías de producción:

Metodología 1: El protocolo de producción convencional realizado en el Modelo hortícola bajo invernadero de Almería reflejado por Honoré et al. [97].

Metodología 2: Un modelo de producción alternativo. Propuesta de una autogestión de los restos vegetales obtenidos durante el proceso productivo. Se contemplan una reducción de las partidas de agua (37.2%), preparación del terreno, gestión externa de los restos vegetales (100%) y desinfectantes químicos del suelo (100%). Sin embargo, se mantiene la fertilización inorgánica de cobertera tradicional.

Metodología 3: Se realizaría la metodología de producción 2, contemplando, además, una reducción total de los fertilizantes inorgánicos durante 215 de los 310 días que dura la fase de crecimiento vegetativo y el periodo productivo.

Tabla 1. Alternativas de cultivo evaluadas económicamente en el periodo 2016-2021.

Alternativas	Serie de cultivos
1	Sandía (2016)[2] + tomate (2016)[1] + calabacín (2017)[2] + pimiento (2017)[1] + sandía (2018)[2] + tomate (2018)[1] + calabacín (2019)[2] + pimiento (2019)[1] + sandía (2020)[2] + tomate (2020)[1]
2	Tomate (2016)[2] + pepino (2016)[1] + berenjena (2017)[2] + judía (2017)[1] + melón (2018)[2] + tomate (2018)[1] + pepino (2019)[2] + berenjena (2019)[1] + melón (2020)[2] + judía (2020)[1]
3	Melón (2016)[2] + pimiento (2016)[1] + sandía (2017)[2] + tomate (2017)[1] + melón (2018)[2] + pimiento (2018)[1] + sandía (2019)[2] + tomate (2019)[1] + melón (2020)[2] + pimiento (2020)[1]
4	Calabacín (2016)[2] + berenjena (2016)[1] + melón (2017)[2] + pimiento (2017)[1] + sandía (2018)[2] + berenjena (2018)[1] + calabacín (2019)[2] + pimiento (2019)[1] + melón (2020)[2] + berenjena (2020)[1]
5	Calabacín (2016)[2] + tomate (2016-2017)[3] + tomate (2017-2018)[3] + tomate (2018)[1] + sandía (2019)[2] + tomate (2019-2020)[3] + tomate (2020)[1]

[1] ciclo de otoño-invierno; [2] ciclo de primavera-verano; [3] ciclo único. Fuente: elaboración propia.

- **Estructura de ingresos y gastos**

La estructura de ingresos y gastos empleados en este trabajo se basó en la propuesta de Honoré et al. [97] que seguía la guía empleada por la finca experimental "Catedrático Eduardo Fernández" de la Fundación UAL-ANECOOP y la sugerida por Toresano y Camacho-Ferre [98] para Agroseguros, S.A.-España. Esta última correspondía a unos datos no publicados obtenidos a casusa de la Prestación de Servicios PS2012000000000184 de la Oficina de Resultados de la Investigación (OTRI) de la Universidad de Almería. Los valores ofrecidos se han actualizado anualmente bajo el índice nacional general ECOICOP (European Classification of Individual Consumption by Purpose).

Análisis estadístico

Se aplicó un tratamiento estadístico que consistió en un análisis de la varianza (one-way ANOVA) tomando como factor el tratamiento aplicado al suelo para evaluar cada una de las variables medidas o calculadas. Con antelación, se comprobaron las asunciones de normalidad y homocedasticidad a través de los test de Shapiro–Wilk y Bartlett, respectivamente, empleándose transformadas matemáticas en aquellos casos en los que no se satisfacían las asunciones indicadas. En algunos casos, no se encontró una transformación de los datos para poder aplicar análisis de la varianza, por lo que se empleó el test no paramétrico de Kruskal-Wallis. Seguidamente, se aplicó la prueba *post hoc* de Test HSD de Tukey para el test ANOVA y una comparación por pares en el caso del test no paramétrico de Kruskal-Wallis. Las pruebas ANOVA y HDS se realizaron a través del software STATGRAPHIC CENTURION XVIII (Manugistic Incorporate, Rockville, Maryland) para Windows, mientras que el test no paramétrico de Kruskal-Wallis y la comparación por pares se realizó mediante el del software Statistix v. 9.0.5 (Analytical Software, Florida, Estados Unidos). Por otro lado, la representación de los resultados se realizó a través del software Sigmaplot v.14.0.

Los datos de la comunidad de hongos (a escala de género) se compararon entre los tratamientos aplicados al suelo mediante un análisis permutacional multivariado de la varianza (PERMANOVA) al finalizar el cultivo de cada año, para observar si existían diferencias significativas entre las comunidades fúngicas de los tratamientos. PERMANOVA es una prueba estadística que calcula matrices de distancia entre fuentes de variación para realizar pruebas de permutación para el análisis de la varianza univarible o multivariable. Esta prueba calcula Pseudo-F para obtener valores de p [99]. Para las comparaciones entre los tratamientos se realizaron pruebas de PERMANOVA por pares a partir de la simulación de Monte Carlo, debido a que eran pocas las permutaciones posibles para conseguir un valor p preciso para las inferencias a un nivel de significación adecuadamente pequeño [100].

1.3.2. Resultados

I. Gestión de los Residuos Plásticos Agrícolas en el Marco de la Economía Circular. Caso de la Agricultura de Invernadero de Almería (España) (The Management of Agriculture PlasticWaste in the Framework of Circular Economy. Case of the Almeria Greenhouse (Spain)-Q1)

La agricultura bajo invernadero de la provincia de Almería genera de maneral anual 1.503,6 kg·ha^{-1}-año^{-1} de residuos y subproductos plásticos en la producción de sus frutas y hortalizas. El plástico empleado en la estructura del invernadero, desinfección del suelo o estructuras auxiliares de producción supone más del 70% de la cantidad anual. El polietileno de alta y baja densidad (LDPE y

HDPE) y polipropileno (PP) son los polímeros plásticos predominantes en masa. Sin embargo, el poliestireno (PS) ocupa un volumen mayor que el polietileno de alta (HDPE) y polipropileno (PP) a consecuencia de las densidades de los compuestos.

Los residuos y subproductos plásticos reciben un tratamiento por un agente externo (i.e., plantas de gestión de plásticos). La provincia de Almería dispone de más de veinticinco plantas que se encargan de almacenar, valorizar y tratar los residuos plásticos. Estas se sitúan mayoritariamente en el poniente almeriense. La oferta de servicios de las plantas de gestión es variada y, en algunos casos, limitada. Los residuos más aceptados son las cajas plásticas, mallas de ventilación, mantas térmicas y tuberías de riego. Desgraciadamente, solo el 30% de las plantas de tratamiento aceptaban los plásticos de cubierta de los invernaderos y desinfección del suelo. Por otro lado, algunas plantas ofertaban un sistema de incentivos focalizado únicamente a los materiales de mayor aprovechamiento (plásticos de cubierta del invernadero, sistema de riego y contenedores de plástico). Posteriormente recibían un tratamiento de reciclaje mecánico (i.e., extrusión) o una valorización energética controlada, adicionalmente, los recipientes de mayor capacidad podían ser reutilizados. Sin embargo, el actual sistema de gestión de plásticos no parece ofrecer una solución íntegra a las necesidades del sector ante los vertidos plásticos que parecen producirse en la actualidad (Figura 4).

No obstante, los agentes que intervienen en el proceso de gestión presentan diferentes oportunidades para mejorar al actual sistema de gestión bajo los principios de la economía circular. Principalmente, los productores disponen de materiales biodegradables o técnicas de cultivo que pueden permitir descender la producción de residuos plásticos (i.e, rafias de entutorado biodegradables, acolchados orgánicos, plásticos biodegradables, etc.), sin embargo, y, debido a la limitación tecnológica actual, algunos materiales como el plástico de estructura no disponen de alternativas. Por ello, deben seguir tratándose y reciclándose a través de los gestores externos. Los agentes de gestión y/o Administración deberían extender la actual oferta de incentivos además de mejorar la canalización de la información requerida por los productores mediante una aplicación móvil. Además, de implementar un sistema de trazabilidad obligatorio.

Por otro lado, obtuvo una relación directamente proporcional entre el precio del petróleo Brent y el porcentaje de plásticos reciclados. En este caso, la Administración, en el marco de la economía circular, debe articular algún sistema de compensación que mantenga la demanda de los fabricantes para la producción de nuevos polímeros basados en material reciclado.

Figura 4. Vertidos plásticos identificados en un cauce de una rambla del poniente almeriense a 20 de junio de 2021.

II. Efecto Repetido de la Reutilización de RestosVegetales de Tomate como Enmienda Orgánica en la Fertilidad del Suelo en invernadero (Effect of Repeated Plant Debris Reutilization as Organic Amendment on Greenhouse Soil Fertility-Q1)

La fertilización a base de 3,5 kg·m^{-2} de restos vegetales frescos de tomate del cultivo anterior obtuvo una producción final comercial y una calidad del fruto similar al cultivo convencional con fertilización inorgánica de cobertera durante los ciclos de producción de tomate de hasta 217 DDT. En el segundo año de ensayo se logró una producción diferenciada entre estos dos tratamientos, sin embargo, se registró una epidemia de *Botrytis cinerea* de imposible control a causa de las condiciones climáticas excepcionales que se registraron durante el mes de diciembre de la campaña 2016/2017, invalidando parcialmente los resultados desde los 170 DDT. La no fertilización obtuvo una producción menor durante los tres años de ensayo a la registrada por la fertilización única con restos vegetales frescos de tomate del cultivo anterior y la fertilización inorgánica.

La aplicación de la técnica solarización o biosolarización provocó un descenso temporal de la microbiota edáfica del suelo. Las bacterias mostraron una sensibilidad menor al tratamiento de desinfección. Los hongos filamentosos registraron un descenso mayor, llegándose en algunos momentos hasta su "cero analítico". Sin embargo, al finalizar el cultivo la microbiota del suelo tenía la capacidad de restablecerse hasta alcanzar un nivel similar al inicial. Aunque, la no adición de restos vegetales (i.e., solarización) mostró una agresividad mayor, y, por consiguiente, una menor capacidad de recomposición.

Figura 5. Morfología vegetal del cultivo de tomate el tercer año de ensayo. A la izquierda se observan los tratamientos que solo recibieron restos vegetales de tomate como abono (PD, PD1 y PD2). A la derecha se observan los tratamientos que recibieron una fertilización inorgánica de cobertera (IF, IFPD e IFPD1). PD: 3,5 kg·m^{-2} de restos vegetales de tomate; PD1: 5 kg·m^{-2} de restos vegetales de tomate; PD2: 6,5 kg·m^{-2} de restos vegetales de tomate; IF: fertilización inorgánica; IFPD: : fertilización inorgánica + 3,5 kg·m^{-2} de restos vegetales de tomate; IFPD1: : fertilización inorgánica + 5 kg·m^{-2} de restos vegetales de tomate

De manera general, las variables físicas del suelo se mantuvieron constantes durante el experimento. No obstante, se registró un descenso de la conductividad hidráulica del suelo, lo que pudo tener una implicación directa sobre la dosis de riego aplicada al cultivo. En cuanto a las variables químicas se incrementó significativamente el nitrógeno total y el contenido en materia orgánica del suelo al final del experimento tras la adición reiterada de restos vegetales de tomate del cultivo anterior. El potasio asimilable ascendió tras aplicar la biosolarización, mientras que las parcelas con fertilización inorgánica de cobertera registraban un comportamiento contrario.

La fertilidad del suelo mejoró paulatinamente con la adición de restos vegetales de tomate y biosolarización. Las plántulas de tomate crecidas en condiciones contraladas en las muestras de suelo donde se había aplicado el subproducto vegetal registraron un ascenso en su área foliar hasta el final del experimento, mientras que la adición de fertilización inorgánica obtuvo un comportamiento contrario.

III. Biodesinfección como Método Rentable de Fertilización para Cultivos Hortícolas en el Marco de la Economía Circular (Biodisinfection as a profitable fertilization method for horticultural crops in the framework of the circular economy-Q1)

La fertilización a base de enmiendas orgánicas (restos vegetales de tomate de la campaña anterior o *pellets* de *Brassica carinata*) lograron una producción final comercial y una calidad del fruto similar al cultivo convencional, incluso cuando este se encontraba combinado con materiales orgánicos (restos vegetales de tomate de la campaña anterior o *pellets* de *Brassica carinata*). Ambos bloques de tratamientos (i.e., bloque PD y bloque IF) alcanzaron una producción final significativamente superior al tratamiento sin fertilización.

Por otro lado, la adición de una mayor dosis de enmienda orgánica no tuvo la capacidad de diferenciar la producción con respecto a la dosis más baja. La producción obtenida entre los tratamientos que formaban parte del bloque PD (PD, PD1, PD2, PDB1 y PDB2) y bloque IF (IF, IFB1, IFB2, IFPD e IFPD1) fue similar entre sí durante los tres años.

Los ensayos realizados en cámara de ambiente controlado revelaron una mejora de la fertilidad del suelo de las parcelas experimentales de los tratamientos donde se realizó una adición reiterada de restos vegetales de tomate (PD, PD1, PD2, PDB1 y PDB2) frente a aquellas que recibieron de una fertilización inorgánica (IF, IFB1, IFB2, IFPD e IFPD1), lo cual se vio reflejado en el área foliar de las plántulas de tomate y pepino. Además, se obtuvo un descenso del consumo de agua del 37,2% en las parcelas donde se aplicaron los restos vegetales de tomate de la campaña anterior.

De manera general, la adición de *pellets* de *Brassica carinata* influyó negativamente sobre el rendimiento económico de los tratamientos donde fueron añadidos a consecuencia del elevado precio del compuesto comercial. Su adición provocó un incremento del 22% del coste de producción, mientras que el uso de los restos vegetales los disminuyó un 4,8%. Así, la reutilización de la biomasa agrícola obtenida del invernadero (i.e, aplicar los principios de la economía circular en lo que refiere a su gestión) tuvo un efecto positivo sobre diferentes componentes del sistema agrícola sin comprometer su rentabilidad, mostrando, incluso un mayor interés que los *pellets* de *Brassica carinata*.

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PUBLICACIONES

CAPÍTULO I: THE MANAGEMENT OF AGRICULTURE PLASTICWASTE IN THE FRAMEWORK OF CIRCULAR ECONOMY. CASE OF THE ALMERIA GREENHOUSE (SPAIN)

International Journal of *Environmental Research and Public Health*

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Article

The Management of Agriculture Plastic Waste in the Framework of Circular Economy. Case of the Almeria Greenhouse (Spain)

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Abstract: In recent decades, ecosystems have suffered diverse environmental impacts caused by anthropogenic activities, including the dumping of plastic waste. This situation has prompted the European Union to introduce a new policy based on the circular economy. In this study, the present state and future perspectives on the generation and treatment of plastic waste in the intensive agriculture of Almeria (Spain) are analyzed. This activity generates 1503.6 kg·ha^{-1}·year^{-1}, on average, of plastic waste with an approximate treatment cost of 0.25 €/kg. The present study shows that the volume of plastic waste from intensive agriculture in Almeria is constantly increasing (48,948.2 tons in 2020/21) and it is suggested that the current management system does not meet the needs of the sector. Although it presents great opportunities for improvement under the framework of the circular economy. Furthermore, this work reports a direct relationship between the price of the raw materials needed for the production of plastic and the volume of recycled plastics. For this reason, it would be advisable for the administration to consider the implementation of a tax rebate system for the sector and specifically when the petroleum derivatives used to manufacture plastic are less expensive, and the recycling option is not so attractive.

Keywords: circular economy; waste management; agriculture; plastic waste; sustainable development

Citation: Castillo-Díaz, F.J.; Belmonte-Ureña, L.J.; Camacho-Ferre, F.; Tello-Marquina, J.C. The Management of Agriculture Plastic Waste in the Framework of Circular Economy. Case of the Almeria Greenhouse (Spain). *Int. J. Environ. Res. Public Health* **2021**, *18*, 12042. https://doi.org/10.3390/ijerph182212042

Academic Editor: Paul B. Tchounwou

Received: 3 October 2021
Accepted: 13 November 2021
Published: 16 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Anthropogenic activities have deteriorated natural ecosystems while compromising their sustainability [1,2]. Among these activities, the production of food and fiber required by humans has led to the transformation of ecosystems into agricultural systems [3], which alters their functionality and organization [4]. These parameters have changed with every agricultural revolution triggering an increase in crop yields [5–10]. This has resulted in an ever-increasing consumption of natural resources [11]. The metamorphosis of agricultural systems has led to a shift from traditional subsistence agriculture to commercial agriculture, especially in the most economically developed countries [12]. This dynamic is causing serious environmental, social, and economic imbalances in some cases [2,13–16]. However, despite the changes that have taken place, agriculture continues to have a family-based structure in most countries and it is a major source of employment as well [17].

Agricultural evolution has led farming systems to demand inputs that are linked to plastic polymers [18–22]. The characteristics of plastic elements make them one of the primary pollutants in ecosystems, mainly due to their tendency to fragment into small particles, such as microplastics and nanoplastics [23–28]; and by the emission, due to ultraviolet radiation from the sun, of some chemical substances that are added during the manufacturing process (additives) to improve the characteristics of the plastic (e.g., biophenol) [29,30]. Unfortunately, the dumping of plastic waste is a common practice and marine ecosystems have experienced the highest incidence of dumping [31,32], which affects their flora and fauna [25], and its associated microbiome [33]; as well as their physical environment [34]. Negative externalities have also affected terrestrial ecosystems and agriculture has become a source of pollution, particularly in the case of intensive agriculture due to the massive use of inputs made from plastics [18,22]. Thus, poor management of this material can lead to the accumulation of microplastics in soil profiles [35] or to the internal infestation of some animals intended for human consumption when fed with agricultural biomass [36], can lead to the accumulation of polymers and chemicals in plant and animal tissues that can be transferred to the food chain [30,37,38]. This may pose a risk to the health of living beings, including humans [26,30,39]. For example, some additives added to plastics have been observed to act as endocrine disruptors (e.g., biophenol) [29,30].

In most cases, the lack of sustainability generated by the conventional agricultural production process contravenes the United Nations (UN) principles for "Sustainable or Lasting Development" formulated in 1992 [40]. In September 2015, the UN approved the 2030 Agenda for Sustainable Development addressing the economic, social, and environmental aspects of greatest global interest [41], which includes the sustainability of agricultural systems [42]. The Agenda has guided the development of various strategies and regulatory bases of its members. In addition, the European Union (EU) proposed the European Green Pact as the central axis of this change to implement a long-term production model based on sustainability [43] by replacing its current linear economic model with an alternative model, such as the circular economy (CE). In 2015, the foundations were laid for a European Circular Economy Action Plan to promote the reduction, reuse, and recycling of inputs used in the various production systems to minimize the waste generated. It details seven lines of action to address the problem generated by waste, which includes plastics [44]. This action plan underwent a revision in 2020 and the lines of action proposed in the previous plan have been completed [45]. These new measures aim to reduce the pollution caused by plastics and they include a ban on single-use plastics, which affects the materials used in food marketing [46]. In addition, the EU has recently reformulated its waste management regulations affecting the treatment of agricultural plastics (hazardous and non-hazardous) [47–50]. These regulations make special mention of the reuse of waste generated in production processes by transforming it into by-products.

Intensive agriculture under plastic, or in greenhouses, is very important on a European scale. More than 43% of the greenhouse area in the world is located in the EU, i.e., about 175,000 ha of the 405,000 ha identified worldwide [51]. Spain, France, Greece, Italy, and the Netherlands are the areas of greatest significance and Spain has the largest area of protected cultivation with 71,783 ha. Protected agriculture is not homogeneously distributed in the country but rather concentrated in agricultural areas [52]. Thus, the province of Almeria is the largest agricultural region of protected crops in Spain reaching 32,554 ha of greenhouses in 2020. These are mostly concentrated into two agricultural regions (Campo de Dalías and Bajo Andarax—Campo de Níjar) [53] that are socioeconomic pillars in the territory [54,55]. Despite being systems that typically consume large amounts of resources [51], they are known for their efficient use of these resources thanks to the technology involved in different production processes [56]. However, they also generate high amounts of different kinds of waste [18,22,57], plastics being one of them [21,22]. For some years now, the Food and Agriculture Organization of the United Nations (FAO) has recommended a series of practices in protected agriculture with the aim of mitigating climate change and promoting the sustainability of the systems [56]. This has been coupled with an effort made by the EU to promote the establishment of "circular horticulture" in agriculture under plastic, which has expanded significantly in its territory [51]. Indeed, the intensive greenhouse horticultural sector has been described as a suitable place for its implementation [57–61]. However, due to the recent introduction of various strategies and action plans, the establishment of circular horticulture is considered one of the biggest challenges of the agricultural systems, including those located in the province of Almeria [62].

Due to the socio-economic importance of greenhouse agriculture in Almeria and its huge need for plastics, it is essential to identify the opportunities of the agricultural system to obtain its production under the principles of CE. Thus, the objectives of this work have been the following:

1. To calculate the production of agricultural plastic waste or by-products in the greenhouse fruit and vegetable production system in Almeria along with the current management system.
2. Identify and qualitatively assess the various existing alternatives for the management of agricultural plastic waste along with the opportunities supported by the current regulatory framework that may exist for farmers and managers.
3. To evaluate the relationship between the price of oil and the amount of recycled plastic in the member States of the EU.

2. Materials and Methods

2.1. General and Specific Stages of the Research Process

For this research, a compilation, classification, verification, and detailed analysis of the information obtained from various studies, technical reports, regulations, and statistics from various public and private organizations was carried out. These organizations had authority and/or relationships with the subject matter addressed and these ranged from local to international. In addition, telephone consultations with numerous departments of regional and local public institutions in charge of managing the data of interest were made to validate the information gathered from their official web pages. Telephone or e-mail interviews were conducted with different agents involved in the production, marketing, or management of agricultural plastics with the aim of expanding and verifying the information found in the bibliography.

The analysis of the literature on plastic waste/by-products was carried out using the Scopus and Web of Science (WoS) databases. This procedure has already been used in other studies related to waste management in agriculture [58] resorting in some cases to the use of specialized software for information processing (Excel Microsoft 365, SigmaPlot 14.0 and SPSS Statistics v.26). Table 1 shows the specific stages of the study.

Table 1. Specific methodology and sources of information consulted.

Objetives		Procedure	Source of Information
1.	To estimate the production of agricultural plastic waste or by-products in the greenhouse fruit and vegetable production system in the province of Almeria, together with the current management system.	Review and analysis of technical studies and scientific research. Contrast of information found by means of the agents qualified to do so. Processing, analysis, and graphic representation of the results (Excel Microsoft 365 and SigmaPlot 14.0).	Official websites of public agencies: CAGPDR, MAPA and ERDF. Websites of public and private research centers: FC and CIAIMBITAL. Scientific literature obtained from search engines such as Scopus and Web of Science (WoS).
2.	Identify and qualitatively assess the various existing alternatives for the management of agricultural plastic waste, together with the opportunities that may exist for farmers and managers, which are supported by the current regulatory framework.	Identification of key agents (public and private organizations). Telephone or email interview with key agents. Review and analysis of technical studies and scientific research. Processing, analysis, and graphical representation of the results (Excel Microsoft 365 and SigmaPlot 14.0). Review and analysis of regulatory bases and strategies at local, regional, national, and international levels.	Information obtained from interviews with CA, IEPA, and ES. Official websites of public and private organizations: CAGPDR, BOE, EUR-lex, MAPA, and SIGFITO. Websites of public and private research centers: IFAFA, CIAIMBITAL, ERDF, and FC. Scientific literature obtained from search engines such as Scopus and Web of Science (WoS).

Table 1. *Cont.*

	Objetives	Procedure	Source of Information
3.	To evaluate the relationship between the price of oil and the amount of recycled plastic in the EU Member States.	Review and analysis of official statistics on crude oil barrel price (series 1987–2020), percentage of "packing" recycled plastic (series 1997–2018) (Article 6.1 Directive 94/62/EC) (consulted on 17 May 2021) and percentage of 'light packaging' recycled in Almería (consulted on 2 November 2021)	Crude oil barrel price: EIA. Percentage of "packing" recycled plastic: Eurostat.Percentage of 'light packaging' recycled in Almería: CAGPDR.
		Statistical processing, analysis, and graphical representation of results (Excel Microsoft 365 and SigmaPlot 14.0 and SPSS Statistics v.26).	Scientific literature obtained from search engines such as Scopus and Web of Science (WoS).

CAGPDR: Consejería de Agricultura, Ganadería, Pesca y Desarrollo Rural; MAPA: Ministerio de Agricultura, Ganadería y Pesca; FC: Fundación Cajamar; ERDF: European Regional Development Fund, REINWASTE project; FC: Fundación Cajamar; CIAIMBITAL: Centro de Investigación en Agrosistemas Intensivos Mediterráneos y Biotecnología Agroalimentaria de la Universidad de Almería; C. A: Cooperativas Agroalimentarias; IEPA: Engineers in charge of the production process of plastics producing companies; ES: Supply companies; IFAPA: Instituto de Investigación y Formación Agraria y Pesquera; EIA: Energy Information Administration of the United States; Eurostat: European Statistical Office.

2.2. Details of the Statistical Treatment Performed for Objectives 1 and 2

After obtaining the data and in view of the variety of publications found on the subject analyzed, the information was processed by synthesizing it into homogeneous groups (i.e., element) as shown by other authors [18,22] and the technical documents of the Reinwaste project [63–67] to ease the representation of the production and management of waste/by-products with the aim of obtaining a single value.

Estimates for Objective 1 were made for commercial "scratch and shake", flat vine and multi-tunnel greenhouses where horticultural crops were grown under the common practices of the area (conventional and organic crops grown on natural soil), from the literature identified in different databases [18,22,63–67]. The data contained in the literature consulted were obtained from an average of plastic waste generated in greenhouses with a surface area of 0.15–1 ha. In these documents, the total production of plastic waste is presented, without indicating the standard deviation. The data are presented in kg-ha^{-1}. Finally, the total production of plastic waste per unit area was also calculated and the total production for the total greenhouse area in 2020 was estimated, according to data provided by the regional government [53].

In order to describe the current plastic waste management system in the province of Almeria, direct consultation with the key agents involved in the process (companies) was used. After analyzing the information collected, the plastic waste managers were classified according to the services they offered. Finally, the mean value and standard deviation of the incentives offered to farmers were calculated, as well as the total cost of plastic waste treatment (€/kg).

The estimate of the average price of plastic waste management was found through the average cost for service, including transportation (€/kg). Finally, the estimate made in Objective 2 for the cost of alternatives was made through information available in the literature (cost + dose) [68,69], the technical documents of the Reinwaste project [63,66,67] and consultation in specialized supply centers to reach the cost increase in €/ha.

2.3. Additional Details of the Methodology for Objective 3

After obtaining the values of the Brent crude oil price per barrel (C), the average annual value was calculated. This value reflects a change in the variable from the time of origin (t) to a monthly lag of twelve months before and after this value (t − 12 to t + 12) to observe the influence of the variable on the annual proportion of recycled plastic (%). The results were expressed in the unit of origin ($/barrel). For this purpose, the following expressions were used:

$$\overline{C_{t-n}} = \frac{\sum_t^n C}{12} \quad (1)$$

$$\overline{C_{t+n}} = \frac{\sum_{t}^{n} C}{12} \quad (2)$$

$\overline{C}$: average price of a barrel of crude oil $\left(\frac{\$}{\text{barrel}}\right)$
t : time (months)
n: number of months of lag time ($-12 \leq t \leq 12$)

The correlation between the values was obtained using Pearson's coefficient (r) with the F test to check the assumptions necessary for its application. The dependent variable was the amount of 'packing' plastic recycled (%) and the amount of 'light packaging' recycled in Almería (plastic, briks and cans; %) and the independent variables were the different annual prices of a barrel of crude oil (t − 12–t + 12; $/barrel). The 27 Member States were then subdivided into two groups (Table 2). The first group included the countries that showed an average Pearson coefficient (t − 12–t + 12) higher than the EU average (G1). The second group included the territories whose average Pearson coefficient (t − 12–t + 12) was lower than this average (G2).

Table 2. Subdivision made in the graphical representation of Pearson's coefficient.

Group	Countries		
G1	Czech Republic Spain The Netherlands Slovenia Sweden Slovakia Belgium	Denmark Estonia Ireland Greece France Croatia Italy	Luxembourg Malta Austria Portugal Finland
G2	Bulgaria Germany Cyprus	Lithuania Romania Latvia	Hungary Poland

Source: own elaboration.

3. Results and Discussion

3.1. Characterization and Estimation of the Production of Agricultural Plastic Waste in the Productive Sector of Greenhouse Agriculture in Almeria

Plastic is linked to most of the components and techniques used in the production process under protection in Almeria (Table 3). It is present in the covering and natural ventilation systems of greenhouses, irrigation equipment and active climate control, agricultural inputs and disinfection processes. It is also used in auxiliary structures such as irrigation ponds and the marketing of the goods [18,22,59–61,63–67,70–72]. The determination of the generation period of this tyspe of waste is established by the crop cycles with a productive seasonality due to their intrinsic characteristics [73,74] Specifically, it was estimated that around 90% of agricultural plastic waste is generated in the province of Almeria between August and September [18].

In detail, it was estimated that agriculture under plastic in the province of Almeria generates an amount of plastic of 1503.6 kg·ha^{-1}·year^{-1} in the production of fruits and vegetables (an annual amount in the system of 48,948.2 t) (Table 3). The amount of waste from covering elements, soil disinfection, and double roofs of greenhouses can account for up to three-quarters of this amount, the rest being made up of the different inputs used in the agricultural system. The packaging of phytosanitary products was classified as hazardous waste while other waste was not classified as such [47,48,75,76]. The increase in the surface area registered in recent years [53,58] would cause an increase in plastic waste or by-products generated in the production process, which is concentrated in a few agricultural districts due to the distribution of the greenhouses. Ninety-one percent of the greenhouse surface area is located in the Campo de Dalías and Bajo Andarax—Campo de Níjar [53].

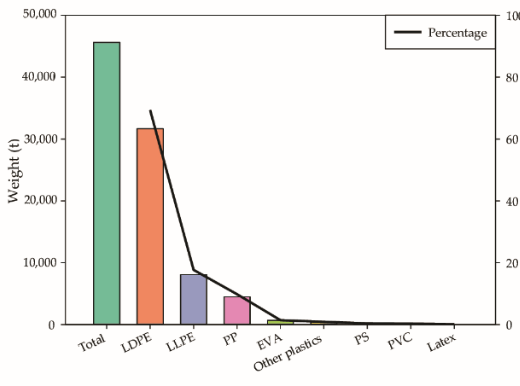
Table 3. Estimation of the production and proportion of agricultural plastic waste/by-products by element and total in the greenhouse production system in the province of Almeria. Values (mean ± standard deviation).

Element	Polymer	Production ($kg \cdot ha^{-1} \cdot year^{-1}$) (n = 5)	Proportion (%)
Structure plastic	LDPE, LLDPE, EVA	707.8 ± 83.3	47.6 ± 2.9
Solarization plastic	LDPE	224.1 ± 29.0	15.4 ± 3.3
Double roof film	EVA	135.2 ± 19.0	8.5 ± 1.4
Irrigation system pipes	HDPE, PVC	113.6 ± 15.1	7.6 ± 0.7
Geotextile netting	PP	64.4 [1]	3.9 [1]
Trellising clips	LDPE	57.9 ± 24.6	4.1 ± 2.6
Trellising raffia	PP	50.6 ± 31.9	3.2 ± 1.9
Chromotropic traps	LDPE	30.4 ± 13.2	2.0 ± 0.8
Ventilation netting	HDPE	23.9 ± 2.9	1.6 ± 0.1
Thermal blankets	LDPE, LLDPE, EVA	15.3 ± 6.0	1.0 ± 0.3
Fertilizers (bags + containers)	LDPE	14.7 ± 5.7	0.9 ± 0.3
Returnable plastic containers	HDPE, PS	14.2 ± 1.0	1.0 ± 0.1
Field boxes	HDPE	13.6 ± 11.0	0.7 ± 0.7
Non-returnable plastic containers	HDPE	9.9 ± 9.2	0.6 ± 0.6
Plastic containers for phytosanitary products	HDPE	9.6 ± 6.7	0.6 ± 0.4
Plastic hives	LDPE	9.2 ± 0.3	0.6 ± 0.1
Gloves	Latex	4.8 ± 4.0	0.3 ± 0.4
Personal protection suit	HDPE	4.0 ± 4.2 [2]	0.3 ± 0.3 [2]
Packaging of biological control products	HDPE	0.4 ± 0.3	0.1 ± 0.0
Total	-	1503.6	-

LDPE: low density polyethylene; LLDPE: linear low density polyethylene; EVA: ethylene-vinyl acetate; PVC: polyvinyl chloride; HDPE: high-density polyethylene; PP: polypropylene; PS: polystyrene. N: number of values. [1]: n = 1; [2]: n = 2; source: own elaboration based on data provided by other authors [18] and technical documents of the Reinwaste project [63–67].

However, as in other models of greenhouse agriculture, these elements were formed from seven groups of polymers, such as low (LDPE and LLDPE) and high density polyethylene (HDPE), polypropylene, ethylene-vinyl acetate (EVA), polystyrene and polyvinyl chloride (PVC) [20–22,77–79]. The different types of polyethylene (LDPE, LLDPE and HDPE) and polypropylene made up the largest tonnage of production (96.9%) (Figure 1). The microplastics obtained from the fragmentation of these polymers cause the greatest impact on the *Posidonia oceanica* meadows found on the Almeria coast. Its ecosystem shows a significant increase in the deposition of microplastics from greenhouse agriculture. The damage caused is not only due to the fragmentation of the material, but also to the presence of various additives in plastic materials, such as benzyl phthalate [80], which can cause harmful effects on the health of organisms [81].

However, due to the density of the compounds, the volume occupied by polystyrene increased significantly from 0.4% of the mass to 25.6% of the volume of plastics generated. This material is mainly generated in the raising of seedlings used in agriculture since it is the main component of the trays used in seedbeds. Thus, the Almeria production system generates between 10.3 and 15.8 g of plastic per kilogram of product (not including the containers used in marketing), which is less than the figure of 20 g observed in other sheltered systems [21].



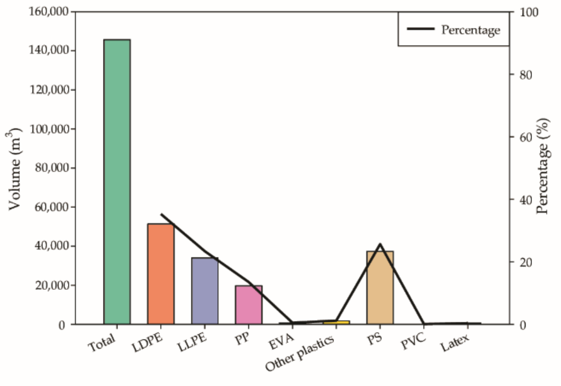


Figure 1. Generation of plastic waste/by-products in the Almeria model subdivided by type of polymer: (**a**) mass estimation; (**b**) volume estimation. LDPE: low density polyethylene; LLDPE: linear low density polyethylene; EVA: ethylene-vinyl acetate; PVC: polyvinyl chloride; HDPE: high density polyethylene; PP: polypropylene; PS: polystyrene. Source: own elaboration based on data provided by other authors [22].

3.2. Management Strategies Used for the Treatment of Plastic Waste from Greenhouses: The Case of the Province of Almeria

The processing of the plastic waste generated in greenhouses in the province of Almeria has raised significant problems throughout the life of the greenhouse model mainly due to the seasonality of waste production, an increase in the greenhouse surface area, the difficulty to manage some plastic waste or by-products, and the bad disposal practices of some farmers [18,63]. In 2001, the dumping of agricultural waste in natural areas of Andalusia resulted in a health crisis that required a cleanup of the countryside in the region of Almeria. This crisis revealed the need to implement an adequate agricultural waste management and treatment system in the province of Almeria in light of the expansion of its intensive agriculture. Since then, competent public institutions have developed different financing lines and agreements for initiatives aimed at the massive collection of agricultural waste. They have also developed urban and rural cleanup plans, along with a general program to improve the integrated management of agricultural waste [18,82]. Despite all efforts, the poor management of agricultural plastic waste or by-products from protected agriculture in the provinces of Almeria, Granada, and Huelva, and the indiscriminate abandonment of these leftovers in natural spaces forced the Government of Andalusia to carry out a campaign to collect greenhouse plastic waste [83–85] in 2018.

Currently, the province of Almeria has more than 25 treatment and recovery centers for hazardous and non-hazardous agricultural plastic waste distributed throughout its territory, most of them located in the western part of the province. In each of these, the storage, waste recovery, or recycling procedures authorized by competent authorities are applied [86]. The necessary decontamination processes are also used for hazardous by-products [76].

Of the farmers who grow crops under shelter in these centers, 96.2% manage plastic waste and 94% are involved in hazardous product packaging [87]. Only 10% of the management centers handle most of the plastic waste generated on farms and they offer a specialized management service. The agricultural plastic waste most readily accepted by the management plants were polyethylene boxes and containers (80%), and ventilation nets (70%), followed by pipes and thermal blankets (60%) (Table 4). In contrast, none of the management centers dealt with gloves, plastic hives, personal protection suits, or chromotropic traps, perhaps as a result of their specialization. Unfortunately, only 30% of the waste management companies accepted the structure, solarization, and double roof plastics, despite the fact that these are the largest fraction in the amount of waste generated in the intensive system. There is a small number of waste management companies handling containers of phytosanitary products and fertilizers used in agriculture. Although management has improved significantly with the implementation of the container take-back system (SIGFITO), to which most manufacturers adhere to, there is still a significant amount of containers that are not delivered to a specific disposal or treatment point [88]. Since 2013, some fertilizer producers have voluntarily joined this integrated treatment system [76], despite not having the regulatory obligation to implement a collective management model or an individual system until 31 December 2024 [48,76].

Table 4. Management offer, incentive system, and possible treatments of waste/by-products in the Almeria model (n = 10).

Element	Management (%) [1]	Incentive [1]		No Incentive [1]			Charge Transportation Costs [1]	Destination [2]
		Proportion (%)	Remuneration (€/kg)	No Charge Proportion (%)	Charge Proportion (%)	Charge Cost (€/kg)		
Structure plastic	30.0	66.7	0.03 ± 0.01	0.0	33.3	0.10	33.3 [3]	A, B
Solarization plastic	30.0	0.0	-	0.0	100.0	0.14 ± 0.05	0.0	A, B
Double roof film	30.0	0.0	-	0.0	100.0	0.14 ± 0.05	0.0	A, B
Irrigation system pipes	60.0	16.7	0.03	66.7	16.6	0.10	0.0	A
Geotextile netting	50.0	0.0	-	0.0	100.0	0.12 ± 0.01	0.0	A, B
Trellising clips	20.0	0.0	-	0.0	100.0	0.15 ± 0.07	0.0	A, B
Trellising raffia	20.0	0.0	-	0.0	100.0	0.15 ± 0.07	0.0	A, B
Chromotropic traps	0.0 [6]	-	-	-	-	-	-	-
Ventilation netting	70.0	0.0	-	0.0	100.0	0.13 ± 0.03	0.0	A, B
Thermal blankets	60.0	0.0	-	0.0	100.0	0.11 ± 0.01	0.0	A, B
Fertilizer bags	20.0	0.0	-	50.0	50.0	0.15 ± 0.07	0.0	A, B
Fertilizes containers	10.0	0.0	-	0.0	100.0	0.39 [4]	-	A, B, C [5], D
Plastic containers [7]	80.0	87.5	0.15 ± 0.03	0.0	12.5	0.10	0.0	A, B
Containers for phytosanitary products	10.0	0.0	-	0.0	100.0	0.39 [4]	0.0	A, B, C [5], D
Plastic hives	0.0 [6]	-	-	-	-	-	-	A, B
Gloves	0.0 [6]	-	-	-	-	-	-	-
Personal protection suit	0.0 [6]	-	-	-	-	-	-	-
Packaging of biological control products	10.0	0.0	-	0.0	100.0		0.0	A
Average management cost	-	-	-	-	-	0.23 ± 0.02	-	-

Source: [1]: own elaboration; [2]: own elaboration based on data provided by other authors [18] and technical documents of the Reinwaste project [63–67]; [3]: only if the amount is higher than 3 t; [4]: price included in the cost of the phytosanitary or fertilizer; [5]: only from containers of products that have agreements with SIGFITO; [6]: the management facilities consulted do not accept this waste. [7]: included are returnable plastic containers, non-returnable plastic containers, field boxes and flower pots. A: recycled; B: energy recovery; C: deposit in the SIGFITO container; D: reuse. Transport costs: 100–150 €/service.

The farmer pays the management and transport costs of plastic waste. The maximum cost of these services has been estimated at approximately 0.25 € for each kg of plastic waste produced as shown in Table 4. Regarding the integrated packaging management system, the cost is incorporated into the sale price of the input [88], while for other types of residue payment is made when the waste is delivered to the authorized disposal facility. Some operators have established economic incentives to motivate the delivery of waste (0.03–0.15 €/kg), although the measure is selective in nature and applies only to some types of waste (mainly from greenhouse coverings, irrigation systems, boxes, and containers).

Subsequently, waste managers commercialize the plastic pellets resulting from the physical recycling processes (extrusion) of these materials [89,90]. However, not all of the by-product obtained meets the quality criteria required by this process, so the remaining fraction can be used for energy recovery due to its high calorific value [64,91–94]. This last method is not considered a recycling protocol [47,50,95]. Some containers of phytosanitary products and fertilizers, generally those with a capacity greater than 200 L, are reused by the companies of origin [96]. It should be noted that some authors recommend that urban waste treatment services manage gloves and chromotropic traps [63,65–67], although this measure leads to a regulatory problem because these residues are defined as non-municipal agricultural waste, so this service falls outside of their range of responsibility [97]. In 2018, in the entire Region of Andalusia, only 40.8% of agricultural plastics were recycled. A total of 43.6% was recovered for further treatment and 15.6% was stored for further recovery [98].

Despite the efforts made by the Andalusian Government, the current plastic waste management model does not offer a comprehensive solution for the sector. The selective nature of the management services available forces farmers to resort to multiple entities, which can confuse the producer and also increase transportation costs. It should be noted that the management centers do not make their rates public, thus increasing the number of preliminary steps to be taken by the farmer. For this reason, some associate or commercial entities facilitate this action with a list containing the most relevant information for the management of agricultural plastic waste, including cost, although this is not a widespread practice. On the other hand, some management centers place obstacles in the treatment of certain types of plastic waste (mainly solarization or mulching plastics) due to the dirt adhered to the plastic, an advanced state of degradation, or the mixture with other types of plastic waste. Therefore, it is recommended that the delivery conditions be agreed upon beforehand between the parties involved [20].

Further, the attitude of some farmers can negatively influence the pre-delivery process. It has been reported that a minority of farmers, often older ones, do not perceive plastic management as critically important for the environment and society [21]. This could lead to the relaxation of sorting and cleaning operations for plastic crop residues, and thus make their treatment more difficult [20].

3.3. Opportunities for Waste Management and Use of Plastic by-Products by the Different Agents Involved: Inclusion in the CE

In recent years, a strategic framework has been developed and accelerated to promote, prioritize, and favor the recovery of plastic by-products generated in agricultural systems. The action plans have been included under the circular economy strategy [44,45,99], so it is required to establish a circular system that performs an adequate management of plastic waste. Therefore, it is also necessary to favor measures that increase the generation of by-products, the introduction of biodegradable plastic, the reduction of plastic needs, or the adequate management of the waste generated.

Different compostable and biodegradable plastic polymers have been recently developed for agricultural use. Unfortunately, their technological limitation only allows their use in a few productive activities, mainly to replace traditional composts in mulching and mulching raffias. Its characteristics enable it to withstand production cycles of up to nine months, which makes it an ideal replacement for mulching used throughout the crop cycle [59,65,66,69]. Other types of biodegradable mulching, such as straw or rice husks, could also be used [68,69]. Biodegradable plastic mulches have shown variable effectiveness compared to conventional polyethylene material when used in soil disinfection by the solarization technique [100,101]. This could be due to the higher permeability of the compound due to its inability to retain heat and moisture [100]. Repeated monoculture can cause reduced plant growth due to soil fatigue [102,103], which increases the need for plastic and disinfection of the agricultural system to avoid significant decreases in production due to the widespread use of solarization in greenhouse agriculture in Almeria [104]. The addition of organic matter [102] or crop diversification [103] can prevent this phenomenon, thus reducing the need for plastic. Some authors have advocated for agricultural biomass as an alternative for organic amendments [57,60,102] or the cultivation of papaya (*Carica papaya*) as an option to decimate the low pluralization of plant species used in the Almeria model [105]. Likewise, the use of alternative plastics, biodegradable polymers in items such as chromotropic traps, trellising rings [22] or flower pots [106,107], or broader reuse in other agricultural inputs sucha s the packaging of phytosanitary products and fertilizers [18] could also be considered. The implementation of this final option would largely depend on the resistance of the material due to the toxicity of the formulations that must be contained. The use of ultrasound emitters instead of adhesive traps [22] or a ring-free trellising methodology, where the plants are only guided through the trellising raffia [60], has also been considered.

The sale price of compostable and biodegradable materials represents a considerable increase with respect to some traditional options (Table 5), but these materials facilitate the management of plastic by-products by the farmer or the management plant. On the other hand, rice husk mulching, incorporated through mechanical banding, and biodegradable raffia have been the alternatives with the lowest price increase. There has been a rise in the number of subsidies to encourage the use of biodegradable and compostable plastic, mainly in mulching and trellising elements. In 2021, farmers who were not affiliated with a Fruit and Vegetable Producer Organization (FVPO) had access to a subsidy for the replacement of mulching raffia of 419.29 €/ha [76,108]. Farmers who were affiliated with an FVPO obtained 50% off their invoice in replacing plastic mulch and 66% off the replacement of trellising elements [109,110]. This has solved a large portion of the cost overrun [111].

Table 5. Economic evaluation for the implementation of available alternatives to plastic for the farmer in the agricultural input market.

Input	Alternative	Cost of the Material (€/ha)	Management Cost (€/ha)		Cost Overrun (€/ha)	Subsidy	Cost Overrun after Subsidy
Padding	Conventional	849.6	70.0		-	-	-
	Compostable	2016.0	19.7 [1]		1116.1	50.0% of the bill	108.1
	Biodegradable	4152.0	19.7 [1]		3252.1		1176.1
	Straw	1933.3	E	1320.0	2333.7	-	2333.7
			D	810.0	1823.7	-	1823.7
			EM	370.0	1383.7	-	1383.7
	Rice husk	1575.0	E	1320.0	1975.4	-	1975.4
			D	810.0	1465.4	-	1465.4
			EM	370.0	1025.4	-	1025.4
Trellising raffia	Conventional	108.9	13.6		-	-	-
	Compostable	622.2	4.5 [1]		504.2	419.2 €/ha o 66.0% of the bill	85.1–93.6
	Biodegradable	559.2	4.5 [1]		441.2		22.1–72.1
Trellising clips	Conventional	130.5	10.2		-	-	-
	Compostable	777.9	6.7		643.9	50.0% of the bill	255.0
	Biodegradable	659.2	6.7		525.2		196.5
Traceability system	Conventional	-	-		-	-	-
	Physical ID document	300.0 [2]	-		300.0	-	300.0
	Document registration system	391.0 [2]	-		391.0	-	391.0
Total	-	-	-		2291.8–4779.7	-	626.7–3073.3

[1] Proportional cost of external management of plant residues; [2] excluding administrative fee. E: sanding; D: bare soil; EM: mechanical sanding. Source: own elaboration based on data provided by other authors [68,69], documents obtained from the Reinwaste project website [63,66,67] and consultations with specialized supply centers.

The use of biodegradable plastic, which decomposes naturally [109], or other organic materials (straw, rice husks, etc.) enables farms to self-manage by incorporating them directly into the soil as raw materials for vermicompost or other types of organic fertilizers. These can act as a part of the nutrient source necessary for the crop [107,112,113] as one of the organic components used in soil biodisinfection processes (i.e., biofumigation or biosolarization) or other agricultural by-products, such as biomass [60]. In fact, the use of alternative materials would facilitate the external management of the biomass or the self-management of the material by the producer by separating any type of plastic from the plant remains [66]. This dynamic would reduce labor by not having to separate the trellising elements from the plant remains. In addition, the inoculation of the soil with earthworms has been recommended to facilitate the proliferation of the microbial flora of the soil by facilitating the biodegradation of the plastic [112]. This practice could provide other benefits as several studies have shown that earthworms improve the physicochemical properties of the soil (improvement of infiltration, porosity, structure or nitrogen mineralization, among others), which allows better crop development [114,115]. On the other hand, organic mulches, such as those formed by straw, offer partially analogous benefits. Their use also leads to an increased organic carbon content [68] and the richness of the fungal community in soil [113], although they should be combined with other amendments or nitrogen compounds to avoid an excessive increase in the carbon/nitrogen ratio.

Unfortunately, no type of compostable or biodegradable plastic whose characteristics meet the needs of resistance and transmissibility demanded by the sector has been commercially developed for the structure of greenhouses, although there are public initiatives to promote its proliferation [116]. Nonetheless, the extension of the useful life of roofing plastics, which is already an ongoing study, could be considered to minimize the generation of waste [117].

Despite the available alternatives, the majority of plastic waste or by-products generated in the greenhouse production system in the province of Almeria must be managed through authorized treatment plants. For this reason, measures such as the establishment of a homogeneous system of incentives to encourage the delivery of waste or a traceability system that allows the identification of those producers who carry out plastic spills should be implemented. A control system has been analyzed by public institutions that is based on physical documentation through a waste management contract and an identification document, or through a documentary record using the compulsory operating logbook in which the information on waste management is entered. This system would facilitate the identification of producers who dump waste [67] and should therefore be introduced as a mandatory measure.

After processing the plastic by-product, the waste management companies obtain a material (plastic pellets) that does not meet the quality criteria demanded by the industry in charge of manufacturing plastic greenhouse coverings. The properties of the recycled raw material are far from those of the basic virgin material [118] and its use would considerably increase production costs while requiring a greater amount of additives and slowing down production process [119]. In some cases, it would also reduce the transmissibility of the cover due to the use of plastic pellets obtained from dyed by-products (e.g., black insect-proof netting). Recycled plastic pellets are marketed at a lower price than virgin material and are destined for a market whose demand is expanding due to current European social and political dynamics [46–48,120] that represent an advantageous opportunity for waste managers [89,120]. The main destination of these is usually the production of some agricultural elements (e.g., planters) or urban furniture (e.g., outdoor furniture, garbage containers) [118,121], although they could also be used for industrial purposes, drums or household items, among others [90,122]. Due to the requirements of physical recycling, a portion of the plastic by-products could be used to obtain energy through energy recovery [92], but unfortunately this protocol causes the emission of large quantities of greenhouse gases, which leads to questions about its sustainability. Current lines of research have investigated the potential of some larvae of tenebrionids

(*Tenebrio molitor*) or lepidoptera (*Galleria mellonella*) to decompose some plastic polymers, such as polyethylene [123–125], but this technology is still under development.

Finally, the parties involved (administration, managers, and producers) should promote and implement the necessary actions to help improve the current system of managing agricultural plastics. These actions should include encouraging the introduction of alternative materials, promoting environmental awareness campaigns to inform producers about the pre-treatment of plastic by-products (management plants, type of service performed, and cost of the service), and a traceability system that allows the identification of producers who discharge waste. For the latter two measures, information technology can be used through a mobile app as well as expanding the incentive system to all plastic waste and by-products generated to offer an amount close to 0.25 €/kg. The last measure is recommended by the EU to encourage the recycling of agricultural plastic waste [99].

3.4. External Influence of the Cost of Oil on the Management of Plastic by-Products: Relationship between the Cost of a Barrel of Brent Oil and the Percentage of "Packing" Plastic

A direct correlation ($p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$) was observed between the price of a barrel of oil and the proportion of recycled plastic (Figure 2) from 1997–2018, although the relationship of the variables depended on each particular European territory.

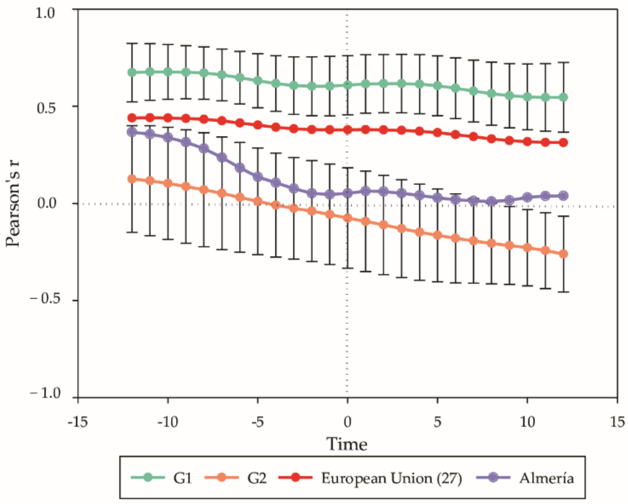


Figure 2. Evolution of Pearson's coefficient in the "packing" plastic ratio versus the monthly cost of a barrel of oil with a monthly lag from t − 12 to t + 12. Source: own elaboration based on data obtained from Eurostat (consulted on 17 May 2021), EIA (consulted on 17 May 2021) and CAGPDR (consulted on 2 November 2021).

Thus, the countries belonging to group G1 achieved the highest ratio coefficients with average values ranging from 54.5% to 67.7% (Figure 2). These values correspond to the ratio at t + 12 and t − 11, respectively. Ireland was the member that showed the highest ratio within this group of territories at 87.9% (in t + 4). Spain reached a ratio that ranged from 47.9–64.1%, while the province of Almeria has a ratio of 36.7–1.0%.

Member states included in G2 obtained a lower ratio than the European average. As in the case of G1, the highest Pearson's coefficient tended to occur in the range between t − 12 and t. However, from t − 4 and beyond, the relationship acquired a negative sign (Figure 2). Thus, countries such as Poland, Germany, and Latvia showed an inverse correlation throughout the range of study. Latvia reported the lowest relationship at t + 12 with −51.3%. The difference shown between the different EU Member States in the ratio could be a result of a disparate application of their plastic waste management and treatment policies [126] where some of the territories would have decoupled their recycling rate from the cost of the raw material.

The results suggest that the Brent price of oil could be an influential variable in the annual planning of European plastic waste management despite targets set by the EU for plastic waste management, which requires its member states to increase the treatment of plastic waste [47,75]. Thus, recycled plastic raw material is offered to the market at a lower cost than that obtained from virgin products [127]. The demand for crude oil from the plastic manufacturing sector [128] could be reduced during periods when the cost per barrel of oil remains high by substituting it with recycled plastic material [129]. However, the relationship observed in Figure 2 also poses difficulties in the face of the volatility shown by the price of crude oil. The increased need for additives in the manufacture of plastic and the slowing down of the production process due to the use of recycled plastics [118] may lead to a sharp drop in demand for the by-product in periods when the price of oil remains low, thus limiting the interest of processing plants to apply a recycling treatment to the polymers delivered. The material could just be sorted, to increase the stock and wait for an increase in the demand for by-products; be used for other purposes, such as energy recovery (which is not legally considered a recycling protocol); or be accumulated in landfills in those European countries where it is allowed [47,48,130–132]. In this case, the Administration, within the framework of the CE, must articulate some compensation system that makes the demand for plastic by-products attractive and maintains the demand of manufacturers for the production of new polymers based on recycled material.

4. Conclusions

Greenhouse fruit and vegetable agriculture in the province of Almeria uses large amounts of plastic in its productive sector. The annual estimate of this fraction was 1503.6 $kg \cdot ha^{-1} \cdot year^{-1}$, which consists of waste and by-products of materials of different origins, but also where the plastics of structure, strips, solarization, and double roof accounted for almost three-quarters of the total. The upward trend in the greenhouse area prompts us to reflect on an increase in the production of waste and by-products in the Almeria model.

Unfortunately, the results of this research suggest that the current system of external management of plastic waste and by-products does not offer a complete solution to the needs of the sector. Despite the significant progress made, plastic dumping still occurs in the natural areas of the province where a negative influence can be seen from all the different parties involved. Nevertheless, the Almeria model would exhibit high potential for improvement since its characteristics seem to facilitate its inclusion within the principles of CE production and thus increase its environmental sustainability. Therefore, it is necessary to facilitate the inclusion of alternative materials and implement the available measures by the Administration to correct the situation, such as establishing a mandatory traceability system in the sector or establishing a system of incentives and compensation to make attractive the delivery of plastic by-products to the manager by the farmer and the demand for recycled plastic chippings by farmers for the production of new materials, respectively. All this under the framework of the EC.

Author Contributions: Conceptualization, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; data curation, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; formal analysis, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; investigation, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; methodology, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; project administration, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; resources, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; software, F.J.C.-D.; supervision, L.J.B.-U., F.C.-F. and J.C.T.-M.; validation, F.J.C.-D., L.J.B.-U. and J.C.T.-M.; visualization, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M.; writing—original draft, F.J.C.-D.; writing—review and editing, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in this article.

Acknowledgments: The authors wish to thank the Doctoral Program in Protected Agriculture of the University of Almeria.

Conflicts of Interest: The authors declare no conflict of interest.

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CAPÍTULO II: EFFECT OF REPEATED PLANT DEBRIS RE-UTILIZATION AS ORGANIC AMENDMENT ON GREENHOUSE SOIL FERTILITY

International Journal of *Environmental Research and Public Health*

MDPI

Article

Effect of Repeated Plant Debris Reutilization as Organic Amendment on Greenhouse Soil Fertility

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Abstract: 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 $kg{\cdot}m^{-2}$ 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

Citation: Castillo-Díaz, F.J.; Marín-Guirao, J.I.; Belmonte-Ureña, L.J.; Tello-Marquina, J.C. Effect of Repeated Plant Debris Reutilization as Organic Amendment on Greenhouse Soil Fertility. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11544. https://doi.org/10.3390/ijerph182111544

Academic Editor: Paul B. Tchounwou

Received: 14 October 2021
Accepted: 31 October 2021
Published: 3 November 2021

1. Introduction

The province of Almeria (Spain) is the part of the world with the highest concentration of greenhouse surface [1–4]. 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 [13–16]. 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 [4,7,17,20–22]. 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 [20–22] 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 [24–26], 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 [20,28–32]. 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 [35–38]. 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].

Previous research has addressed the study of the incorporation of plant debris of different origins into the soil with subsequent solarization on agronomic variables and also on edaphic variables that determine the health and fertility of the soil, although normally the studies address these variables in isolation and/or under different conditions. However, the information obtained from the study of specific plant material on all of these variables is scarce. This information would help the practice of self-management of plant debris in the Almeria Model in accordance with the principles of the circular economy. This would contribute to the sustainability of agrosystems while providing a solution to the problem that the management of this material has posed up until now. Therefore, the objective of this research was to evaluate the effect of the repeated incorporation of tomato plant debris into the soil with subsequent solarization as the only nutrient source during three lengthy tomato production cycles on several variables, including production, crop quality, physical, chemical, and biological qualities of the soil, and also the vigor of tomato and cucumber seedlings grown under controlled conditions.

2. Materials and Methods

2.1. Location, Climate and Greenhouse

The trials were conducted during three consecutive years (2015–2016, 2016–2017, and 2017–2018 seasons) in the facilities of the UAL-ANECOOP Experimental Farm located in the province of Almeria (Spain), the largest Mediterranean greenhouse growing region and the main greenhouse tomato production area in the EU. The experimental greenhouse was representative of the Mediterranean "Raspa y amagado" greenhouse [8] with a maximum and minimum height of 4.70 and 3.40 m, respectively. The greenhouse cover was made of 200 µm thick transparent polyethylene, with zenithal side windows, which included an anti-strip mesh. The greenhouse had a surface area of 1784 m^2 and a northwest-southwest orientation as well as the crop rows. The irrigation system consisted of two totally independent sectors. The nominal flow rate of the emitters used was 3 $L \cdot h^{-1}$. The greenhouse soil consisted of a mixture of gully soil and sand. At the beginning of the study, the soil had 8.8 ± 6.2% of clay, 76.0 ± 4.1% of sand, and 7.0 ± 0.8% of silt. The soil pH was 7.80 ± 0.22, the organic matter content 0.93 ± 0.14%, the carbon/nitrogen (C/N) ratio 7.0 ± 0.8, the amount of active limestone 3.9 ± 1.5%, the amount of carbonates of 26.8 ± 3.1% and the values of primary macronutrients (N/P/K) of 0.078 ± 0.014% N, 79.00 ± 10.98 $mg \cdot kg^{-1}$ P, and 259,29 ± 162,08 $mg \cdot kg^{-1}$ K. The soil had been free of edaphic diseases during the previous two years [20].

2.2. Cultivation, Experimental Design, and Description of Treatments

Three consecutive winter tomato cycles were undertaken, with a duration of 215, 212, and 217 days after transplanting (DAT), respectively. Transplanting was carried out during the first week of September in each of those three years. The tomato varieties used were (*Solanum lycopersicum* Mill.) and "Pitenza F1" (Enza Zaden, Enkhuizen, The Netherlands) with a planting density of 2 plants/m^2. Cultural practices were in accordance with the recommendations offered by Camacho-Ferre [42]. The plants were guided with raffia ropes without using trellising clips. Pest and disease control was carried out in compliance with integrated production (IP) regulations [42].

The treatments applied were based on crop nutrition. Three treatments were considered: (1) conventional inorganic fertilization (i.e., IF), based on Steiner's ideal nutrient solution [43] until reaching an electrical conductivity of 3 $dS \cdot m^{-1}$ (water + nutrient solution); (2) fertilization with fresh tomato plant debris from the previous season at a rate of 3.5 $kg \cdot m^{-2}$ (i.e., PD); and (3) exclusive irrigation water supply without fertilization (i.e., test) (Table 1). The experimental design corresponds to a single-factor design with four replications (n = 4).

Table 1. Nutrient sources used in the different experimental plots.

Nutrient Source	Composition
Irrigation water (test, IF, and PD)	E.C: 0.48 ± 0.03 $dS \cdot m^{-1}$; NO_3^-: 0.04 ± 0.00 $mmol \cdot L^{-1}$; $H_2PO_3^-$: 0.03 ± 0.00 $mmol \cdot L^{-1}$; K^+: 0.08 ± 0.01 $mmol \cdot L^{-1}$; SO_4^{2-}: 0.07 ± 0.00 $mmol \cdot L^{-1}$; Ca^{2+}: 0.34 ± 0.01 $mmol \cdot L^{-1}$; Mg^{2+}: 0.19 ± 0.00 $mmol \cdot L^{-1}$; HCO_{3-}: 0.89 ± 0.12 $mmol \cdot L^{-1}$; CO_3^{2-}: 0.40 ± 0.00 $mmol \cdot L^{-1}$; Cl^-: 3.36 ± 0.40 $mmol \cdot L^{-1}$; Na^+: 2.98 ± 0.58 $mmol \cdot L^{-1}$.
Nutrient solution (IF)	CE: 3.00 $dS \cdot m^{-1}$; NO_3^-: 18 $mmol \cdot L^{-1}$; $H_2PO_3^-$: 1.5 $mmol \cdot L^{-1}$; K^+: 10.5 $mmol \cdot L^{-1}$; SO_4^{2-}: 5.25 $mmol \cdot L^{-1}$; Ca^{2+}: 6.75 $mmol \cdot L^{-1}$; Mg^{2+}: 3 $mmol \cdot L^{-1}$.
Tomato plant debris (PD)	OM: 51.8%; N: 1.86%; P: 2.69%; K: 8.94%; Mg: 1.31%; Ca: 6.41%; Na: 1.60%.

E.C: electrical conductivity; OM: organic matter.

Over the course of the three-year study, solarization treatments were applied to the entire surface of the greenhouse during the summer and prior to crop establishment. Previously it was only in the experimental plots of the PD treatment that the remains of tomato plants were applied. To do this, the tomato plants from the previous crop were separated from the raffia used for trellising and deposited on the central concrete aisle of the greenhouse. The tomato plant debris were then crushed with a hammer chopper, which was applied at a rate of 3.5 $kg \cdot m^{-2}$ over the surface of the four experimental plots, and then mixed using a cross and surface pass (20–30 cm deep) with a rotovator. Once the irrigation branches were in place, the entire surface of the greenhouse was covered with transparent polyethylene plastic at a thickness of 50 μm. To prevent the loss of humidity and gases generated during the biodecomposition of organic materials, the polyethylene cover was sealed around the perimeter with a rectangular trench measuring 0.20 m at the base and a height of 0.30 m. The plastic sheets were then joined with staples and the greenhouse posts were sealed with adhesive tape. After all the above steps were completed, consecutive irrigation was applied for four days until the soil reached the saturation point (56 $L \cdot m^{-2} \cdot year^{-1}$). The solarization treatments continued from June through September.

The area of the experimental plots covered 40 m^2 (80 plants each) for the IF and PD treatments and half for the test treatment.

2.3. *Analyzed Variable*

2.3.1. Crop Yield

Various production parameters were calculated from the first harvest at 92 DAT in the first year and at 99 DAT in the second and third years in calculating the point production of each harvest, accumulated production, and fruit weight. The evaluations were carried out during the 14th, 15th, and 18th harvests of each of the three seasons, respectively. Fruit weight was obtained from the measurement of 25 randomly selected fruits in each harvest. For this purpose, a scale (Mettler Toledo, Columbus, OH, USA) with a sensitivity of 0.1 g was used. Harvesting was carried out in accordance with the commercial maturity criteria required by the marketing entity.

2.3.2. Fruit Quality

Tomato fruit quality was evaluated on five occasions in each of the seasons (at 106, 134, 173, 194, and 215 DAT in the first year; at 127, 142, 170, 184, and 198 DAT in the second year; and at 126, 147, 168, 196, and 217 DAT in the third year). For each evaluation, ten tomatoes were selected from each experimental unit analyzing a total of 200 tomatoes from each treatment per year. The variables evaluated included equatorial diameter using a digital caliper with a sensitivity of 0.01 mm (Mitutoyo; Kanagawa, Japan), mean fruit flesh firmness obtained from three equidistant points and on a surface of 0.5 cm^2 using a durometer with a sensitivity of 0.001 $kg \cdot cm^{-2}$ (Penefel DFT14, Agrosta, Compainville, France), fruit pulp pH with a 0.01 sensitivity pH meter (pH-25, Crison, Barcelona, Spain), and soluble solids content (TSS) in the fruit pulp using a 0.1 brix (pal-1, Atago, Tokyo, Japan).

2.3.3. Evaluation of Soil Variables

Sampling and Soil Samples

Soil sampling was carried out at seven different times throughout the study. The first was conducted at the beginning and prior to the application of solarization to determine the initial conditions of the soil. The remaining samples were distributed evenly over the three years of the trial at a rate of two per year, which coincided with the day solarization treatments were completed (first week of September) and at the end of the crop (second week of April).

Soil samples ($\approx$10 kg each) were collected with a shovel at three equidistant points located on the central crop line of each experimental unit. The samples were then mixed and homogenized in a transparent polyethylene bag and kept refrigerated (8 °C) until processing and/or analysis.

Analysis of Fungal and Culturable Bacterial Microbiota

- Preparation of soil samples:

Soil samples were subjected to a drying, crushing, and sieving treatment under the recommendations offered by Tello-Marquina et al. [44]. They were placed in plastic trays where they were left to dry at room temperature (20–25 °C) for 7–10 days until constant weight. They were then crushed using a porcelain mortar and the resulting product was sieved with a 200 µm. The instruments used were washed and disinfected by flaming with alcohol between samples.

- Analytical method:

The soil culturable fungal and bacterial microbiota was analyzed by the successive dilutions method [44]. This technique was selected to isolate the live culturable fraction and to allow the study of its functionality [45]. The culture medium used was agar-malt acidified with a 1% citric acid solution to a pH of 4.8 to avoid excessive bacterial growth. Ten subreplicates (i.e., *Petri* dishes) of each soil sample were made at 10^{-3} and 10^{-4} dilutions. The *Petri* dishes (9 cm diameter) were incubated at room temperature (20–25 °C) for 4–7 days. Subsequently, total colony forming units (CFU) of fungi and bacteria were quantified and morphological identification at the genus scale of the fungi found in each *Petri* dish was performed [46,47], eventually expressing the results CFU/g dry soil. For the description of the fungal community structure at the end of cultivation in the three years of study, five classical diversity indices were selected: Simpson's diversity index [48], Shannon–Wiener's diversity [49], Margalef's index [50], Pielou's Equity index [51] and number of genera.

Fungi of the genus *Fusarium* were isolated using the Warcup technique with a semi-selective culture medium of Komada [52] modified by Tello et al. [44]. Sixteen Petri dishes per sample were used and they were divided into four blocks of four plates. Incubation was performed at room temperature (20–25 °C) for 4–7 days. The total number of CFU's was quantified and morphological identification was performed at species scale following the taxonomic criteria of Nelson et al. [53] and Leslie and Summerell [54] finally expressing the results CFU/g soil.

Physicochemical Analysis

The determination of the physical and chemical parameters of the soil samples was outsourced to the Agroalimentary Laboratory of Granada of the Ministry of Agriculture, Fisheries, and Rural Development of the Junta de Andalucia. The evaluations were carried out using the standardized methods described in Order 5/12/1975 [55] from a soil subsample of 0.5 kg. These evaluations were performed on soil samples from three experimental plots, in the case of the IF and PD treatments, and from one experimental plot in the test treatment.

Soil organic carbon (SOC) was found by oxidation of the element with potassium dichromate in the presence of sulfuric acid using a 0.5 g sample of soil. Subsequently, soil organic matter (SOM) content was estimated from the Waksman factor (i.e., 1.724).

Total soil nitrogen (Nt) was obtained by the Kjeldahl method modified by Olsen from a 5 g sample of soil that had been sieved through a 1 mm beam sieve. Before digestion of the organic nitrogen, a reduction of the nitric form to ammoniacal was carried out to obtain the Nt content. Assimilable phosphorus (P) was calculated through its solubility in sodium bicarbonate from a 5 g soil sample. Assimilable potassium (K) was found from the capacity of this element to solubilize in a solution of ammonium acetate, for which a soil sample of 5 or 10 g was used, selecting the amount of K present in the sample, choosing 5 g when it was higher than 500 ppm.

The active limestone content was determined using the Bernard calcimeter technique, comparing the volume of carbon dioxide released by a 5 g soil sample; and pure calcium carbonate, 0.1 g, diluted in 250 mL of ammonium oxalate, respectively. The amount of carbonate was also determined by the aforementioned technique, using in this case a 2.5 g sample of previously crushed soil.

The pH and electrical conductivity (E.C) of the soil were determined through the saturated paste using a pH meter and a conductivity meter, respectively. The saturated paste was prepared from a 250 g soil sample and 100 mL of distilled water.

The texture of the samples (amount of sand, silt, and clay) was obtained using the improved bouyoucos protocol from a 40 g soil sample which was sieved until it was composed of 2 mm diameter particles, subsequently following the USDA soil classification for particle size. Finally, the hydraulic conductivity of the soil at saturation (K_h) was estimated from the model proposed by Saxton and Rawls [56] that used the values offered by the texture of the samples and their SOM content in its calculations.

2.3.4. Evaluation of Seedling Growth in a Controlled Environment Chamber

Definition and Plant Material

A pot experiment was conducted to evaluate the impact of the soil on the growth of horticultural plants. The main purpose was to determine if the growth variables evaluated were related to the physical, chemical, and microbiological variables of the soil, depending on treatment. The horticultural species used were cucumbers (*Cucumis sativus cv.* Marketmore 76; Ramiro Arnedo S.A, Calahorra, Spain) and tomatoes (*Solanum lycopersicum* L. *cv.* Rio Grande; Ramiro Arnedo S.A., Calahorra, Spain). The methodology described by Marín-Guirao et al. [25] was used. Due to sample conservation problems, the evaluations were not performed with the soil sampled at the end of cultivation in the third year of the study.

Description of the Experiments

The trials were carried out in a controlled environment culture chamber with a photoperiod of 14 hours of light per day using low-pressure mercury vapor lamps and a luminous flux of 12,000 lm and temperature ranging between 21 °C and 25 °C. Each plant species was planted independently in 200 cm^3 cylindrical pots (experimental unit) at the rate of 1 seed per pot. The pots contained the soil to be studied mixed with vermiculite in a 2 (soil):1 (vermiculite) v/v ratio and 5 replicates of each soil were made for each vegetable species. Seeds were previously disinfected with a 20% solution of commercial sodium hypochlorite (40 $g{\cdot}L^{-1}$) for 15 min and then rinsed with water. The trials lasted 30 days during which irrigation was applied on demand without using any fertilizer. The trials with the different soils (i.e., test, IF and PD) were repeated twice over time for each sampling.

Variables Analyzed and Measurement Process

The five variables that based on previous studies [24,25] were found to be the most representative and constant were evaluated at the end of the trials. These variables included the number of leaves, seedling height, root dry weight, aerial dry weight, and leaf area. Each cucumber and tomato seedling had any dirt removed by careful cleaning with water and was then fragmented into two portions: aboveground and belowground. They were then placed on filter paper and then put in a J.P-Selecta Dry-Big 2003720 oven (Barcelona, Spain) for 48 hours at a constant temperature of 72 °C to determine the dry weight using a Metter Toledo PB 303-S balance (Columbus, OH, USA) with a sensitivity of 0.001. Leaf area was determined using the free software ImageJ 1.48 (NIH Imagen, Bethesda, Maryland) after scanning leaves and leaflets with an Epson Perfection 1240 optical reader (Epson, Suwa, Japan). The number of leaves was quantified at the beginning of the process.

2.3.5. Statistical Analysis

An analysis of variance (one-way ANOVA) was applied to compare the effect caused by the treatments applied to the soil (i.e., test, IF, and PD) for each of the variables analyzed (i.e., tomato fruit production and quality parameters, plant vigor parameters in a controlled environment chamber, and microbiological parameters). Previously, the assumptions of normality and homoscedasticity were tested using the Shapiro–Wilk and Bartlett tests, respectively. Likewise, Student's t-test was used in cases where only two factors were compared (i.e., physical, and chemical parameters). The data were transformed in those cases where the requirements of the parametric test were not met. Kruskal–Wallis nonparametric test was used in cases where the data transformation was not sufficient to meet the assumptions. Tukey's HDS post hoc test (in the parametric tests) and a pairwise comparison (nonparametric tests) was then applied to perform a pairwise comparison between the means and medians of the treatments, respectively, at a 95% confidence level. ANOVA and Tukey's HDS tests were performed with the statistical package STATGRAPHIC CENTURION XVIII (Manugistic Incorporate, Rockville, MD, USA) for Windows while nonparametric tests (Kruskal–Wallis) were performed using Statistix v. 9.0.5 software (Analytical Software, Tallahassee, FL, USA).

Different stepwise linear regression models were calculated to determine the most relevant variables in the prediction of the plant vigor parameters evaluated (dependent variables) in the controlled environment chamber trials. The independent variables (i.e., predictor variables) considered were all the physical and chemical parameters determined in this study. The adjusted R^2 value of each model was calculated to observe the reliability of the prediction. In addition, the statistical importance and significance of each predictor variable were determined through the adjusted and unadjusted beta coefficients and the t-test, respectively. The necessary conditions for the application of the stepwise regression model were assessed visually through the residual plots [57]. In this case, data processing was performed through the SPSS v. 26 statistical package (IBM, Armonk, NY, USA).

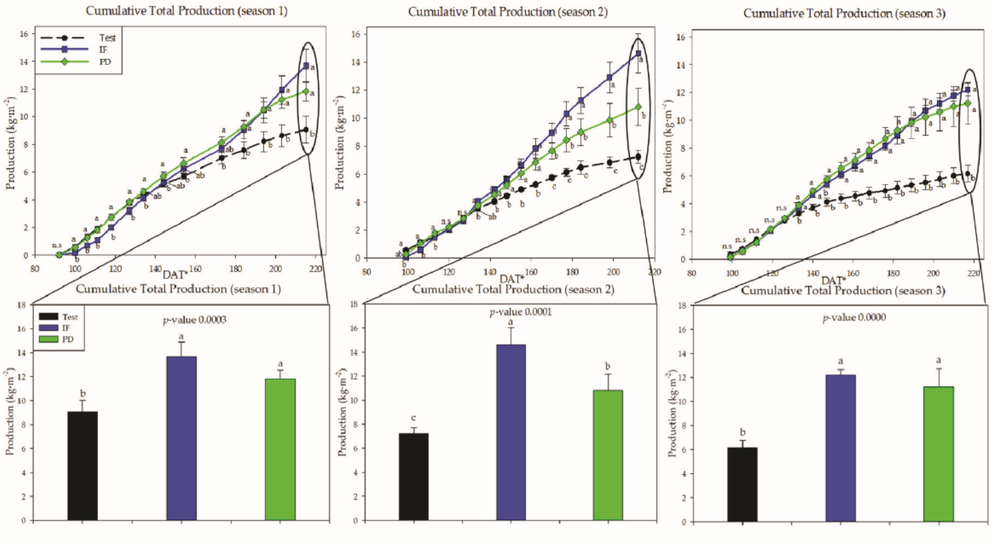
Fungal community data (at the genus scale) were compared among treatments (based on crop nutrition) using permutational multivariate analysis of variance (PERMANOVA) at the end of each year's crop. PERMANOVA is a statistical test that calculates distance matrices between sources of variation to perform permutation tests for univariate or multivariate analysis of variance. This test calculates pseudo-F to obtain *p*-values [58]. For comparisons between treatments, pairwise PERMANOVA tests were performed from Monte Carlo simulation since there were few permutations possible to obtain an accurate *p*-value for inferences at an appropriately small significance level [59].

3. Results

3.1. Crop Production and Quality

Fertilization plans applied on the experimental plots (test, IF, and PD) significantly influenced the cumulative commercial production of tomato plants (Figure 1). In the three years studied, the production obtained from the plots that did not receive any fertilizer (test) was lower than that obtained from the plots that did receive fertilizer. Likewise, in Years 1 and 3 no differences were observed between PD and IF, but there were differences in Year 2 from 170 DAT and after in favor of the treatment with inorganic fertilizer (IF). The interpretation of the behavior of the accumulated production at the end of the second crop must be made taking into account that there was a *Botrytis cinerea* epidemic that was impossible to control due to environmental conditions (temperature and relative humidity). The mycosis began to produce symptoms and to cause production losses from 100 and 170 DAT, respectively. This epidemic did not occur neither in the first nor in the third campaign (mortality of the disease in the first and third campaigns was 0.0–1.5%, while in the second campaign it was 21.4 $\pm$ 10.34% for test, 41.1 $\pm$ 25.1% for IF, and 33.4 $\pm$ 4.4% for PD). A decrease in production was observed for all treatments between the first and third cycle, being 34.98% for test, 17.34% for IF, and 9.26% for PD.

In general, average yield per harvest showed a behavior analogous to that observed for final cumulative yield (Table 2). The IF and PD treatments showed similar fruit weight and diameter beginning with the second season. Non-fertilization had a negative influence on both parameters starting from the first growing season. Similarly, the interpretation of the results of the second year of the trial should be made taking into account the *Botrytis cinerea* epidemic that affected the tomato plants during the second season. The fertilization plans (test, IF, and PD) did not seem to influence the parameters of firmness, soluble solids, and acidity of the fruits due to the expression of a variable or uniform response of the parameters during the production cycles.



(**a**) (**b**) (**c**)

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.

Table 2. Tomato fruit yield and quality parameters in the three years of study (September–April cycles) as a function of crop nutrition. Values (mean ± standard deviation).

		Mean Yield ($kg{\cdot}m^{-2}$)	**Fruit Weight (g)**	**Size (mm)**	**Firmness ($kg{\cdot}m^{-2}$)**	**Soluble Solids (○Brix)**	**Fruit Acidity (pH)**
Season 1	Test (n = 4)	0.65 ± 0.07 b	108.20 ± 4.17 b	58.36 ± 0.40 c	5.15 ± 0.28 a	5.46 ± 0.14 a	3.91 ± 0.04 b
	IF (n = 4)	0.98 ± 0.09 a	125.18 ± 11.05 a	63.53 ± 0.79 a	4.50 ± 0.19 b	5.01 ± 0.08 b	4.03 ± 0.03 a
	PD (n = 4)	0.85 ± 0.05 a	115.82 ± 4.33 ab	60.84 ± 1.00 b	4.56 ± 0.18 b	5.47 ± 0.11 a	4.01 ± 0.03 a
	p-value	0.0003	0.0276	0.0000	0.0043	0.0003	0.0012
Season 2	Test (n = 4)	0.48 ± 0.03 c	99.06 ± 4.87 b	56.59 ± 1.67 b	5.08 ± 0.20 ab	5.50 ± 0.21	4.20 ± 0.02
	IF (n = 4)	0.97 ± 0.10 a	126.59 ± 3.87 a	62.66 ± 0.56 a	4.84 ± 0.16 b	5.28 ± 0.19	4.23 ± 0.05
	PD (n = 4)	0.72 ± 0.09 b	114.70 ± 11.05 a	60.29 ± 2.52 a	5.38 ± 0.20 a	5.53 ± 0.36	4.17 ± 0.06
	p-value	0.0000	0.0016	0.0030	0.0104	0.3788	0.2417
Season 3	Test (n = 4)	0.34 ± 0.03 b	72.10 ± 4.10 b	50.18 ± 1.13 b	5.33 ± 0.21 a	5.64 ± 0.11	3.85 ± 0.03
	IF (n = 4)	0.68 ± 0.02 a	104.70 ± 4.80 a	59.18 ± 1.04 a	4.78 ± 0.88 ab	5.54 ± 0.15	3.85 ± 0.02
	PD (n = 4)	0.62 ± 0.08 a	95.60 ± 10.80 a	56.71 ± 2.43 a	4.00 ± 0.41 b	5.58 ± 0.25	3.89 ± 0.03
	p-value	0.0000	0.0003	0.0001	0.0285	0.7636	0.1588

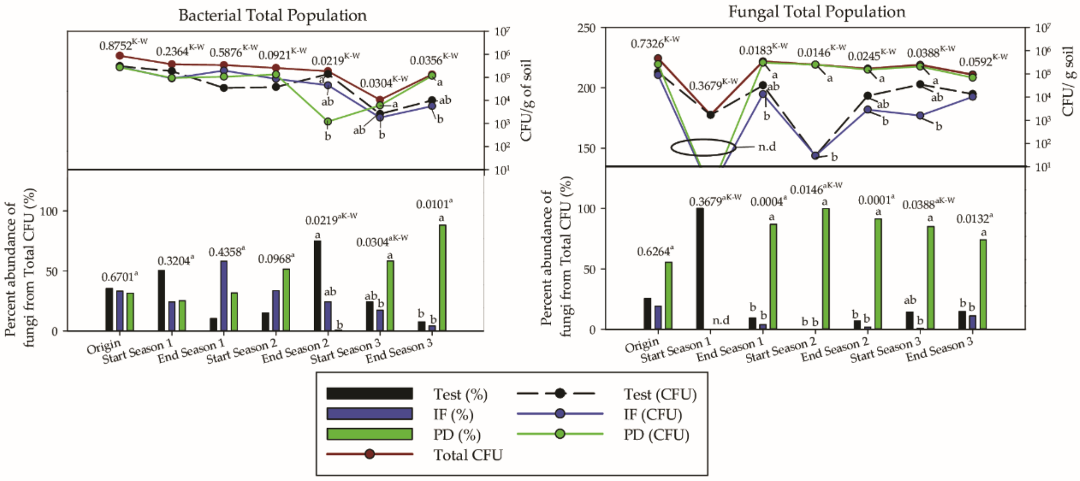
Inorganic fertilization (IF); tomato plant debris (PD); no fertilization (test). Different letters between columns and seasons indicate significant differences. ($p \leq 0.05$, Tukey's HDS test).

3.2. Soil Microbiota

The study of soil microbiota was aimed at finding a relationship between the addition of tomato plant debris and its influence on crop productivity [25]. It was also intended to know whether the effect of solarization with or without organic amendment caused a degradation of the arable soil microbiota [60].

3.2.1. Total Population (Bacteria and Fungi)

Figure 2 enables a reading of the results that are repeated in the three years of experimentation. Solarization with or without tomato plant debris significantly decreases the density of culturable bacteria and fungi. At the end of each analysis campaign a significant increase in soil microbiota is observed, and this recovery is more evident in those plots where tomato plant debris were added.



(**a**) (**b**)

Figure 2. Soil microbiota in the three years of study (September–April cycles) as a function of crop nutrition: (**a**): total bacterial population (CFU and percentage abundance); (**b**): total fungal population (CFU and percentage abundance). 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), [a]: $arcsen(\sqrt{x})$; [K-W]: Kruskal–Wallis test).

The reiterated addition of tomato plant debris (PD) during three consecutive years modified the population of culturable soil bacteria, significantly increasing their relative abundance compared to inorganic fertilization (IF) and no fertilization (test), which registered a decrease throughout the experiment (Figure 2). At the end of the trial, the density of bacteria in the plots that received the PD treatment showed the same order of magnitude as at the beginning of the study (10^5 UFC/g of soil). The test decreased by one order of magnitude and IF by two orders of magnitude.

General speaking, soil solarization treatments had a depressive effect on fungal populations. This effect was more evident during the first year of the trial where no fungal CFU was detected in the soil of the PD and IF plots by the analytical technique used (Figure 2). However, in the second and third years this effect was not so evident in the plots that received tomato plant debris, although it was detected in the soil of the test and IF plots. The fungal population of PD surpassed test and IF at some points by one or two orders of magnitude, although at the end of the trial all treatments reduced their concentration by one order of magnitude. The PD treatment reached a higher relative abundance of filamentous fungi than IF from the end of the first trial.

Nineteen different fungal genera were identified by morphology during the trial, three of which (*Botryotrichum* spp., *Geotrichum* spp. y *Phomopsis* spp.) were only isolated in the initial analysis before the first solarization treatment. Only *Aspergillus* spp. and *Cladosporium* spp. tended to be isolated in all treatments after solarization (Figure 3). At the end of cultivation this number increased to six (*Acremonium* spp., *Aspergillus* spp., *Cladosporium* spp., *Fusarium* spp., *Penicillium* spp., and *Rhizopus* spp.). Three of them (*Acremonium* spp., *Aspergillus* spp. *Fusarium* spp.) were found in the plots that received tomato plant debris at all sampled times, which did not occur in the plots without fertilization or with inorganic fertilization. After the first solarization treatment, and considering the rest of the trial, the plots with tomato plant debris presented the highest number of filamentous fungi (13 genera). In general, *Aspergillus* spp. was the fungal genus that reached the highest expression at all times of analysis and treatments while accounting for an average of 61.4% of the CFU/g of soil.

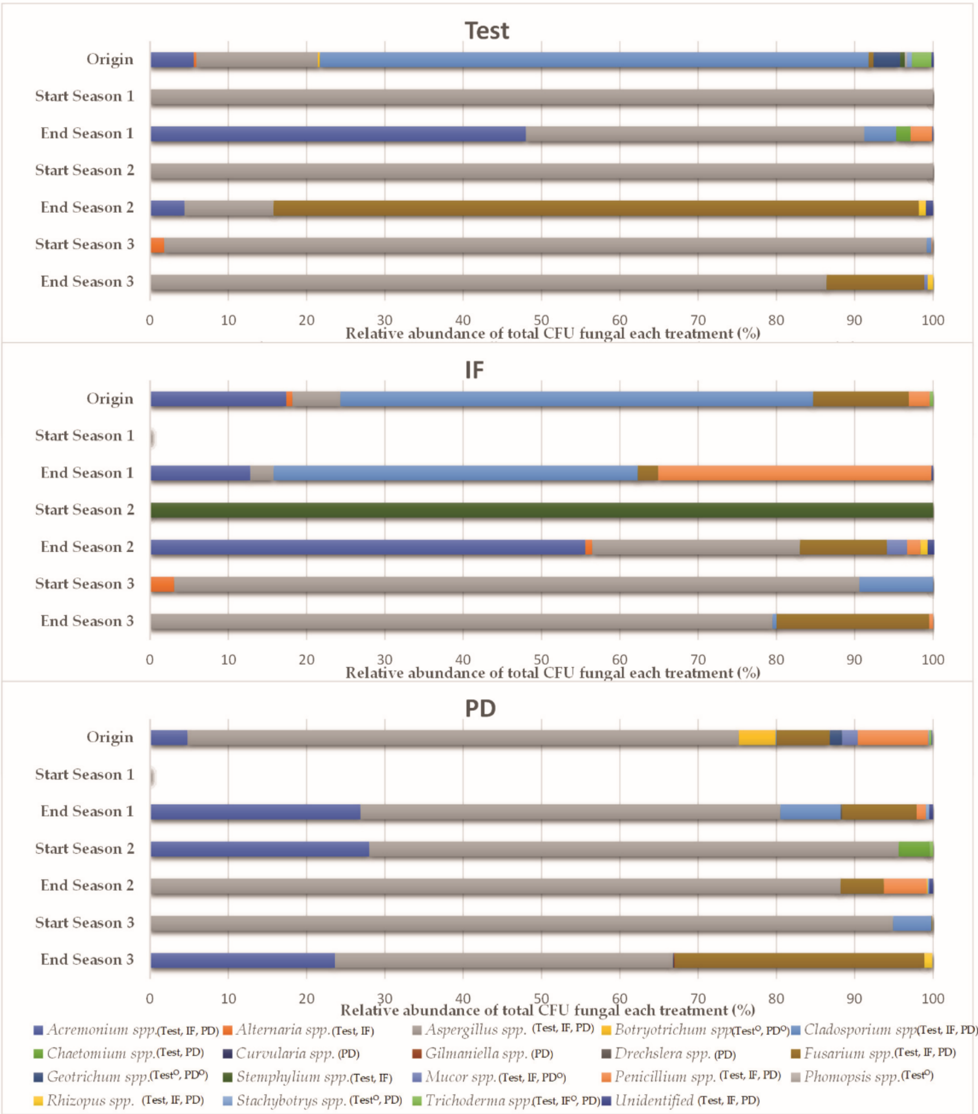


Figure 3. Relative abundance of fungal genera in the three years of study (September–April cycles) as a function of crop nutrition. Inorganic fertilization (IF; n = 4); tomato plant debris (PD; n = 4); no fertilization (test; n = 4). Values (average). ^{O}: isolated only in the initial sampling.

3.2.2. Descriptive Variables of the Fungal Community

None of the descriptive variables of the fungal community showed differences among the different treatments (test, PD, and IF) during the three years of this study (Table 3). In general, the descriptive parameters of the fungal community showed a decrease for all treatments at the end of the trial compared to those observed at the beginning of the experiment.

Table 3. Biodiversity indices of the fungal community in the three years of study (September–April cycles) as a function of crop nutrition. Values (mean ± standard deviation).

Sampling	Treatments	Simpson's Diversity Index	Shannon–Wiener's Diversity	Margalef's Index	Pielou's Equity Index	N° of Genera
Origin	Test (n = 4)	0.52 ± 0.18	1.07 ± 0.45	0.45 ± 0.14	0.59 ± 0.20	6.00 ± 1.00
	IF (n = 4)	0.45 ± 0.13	0.89 ± 0.28	0.33 ± 0.11	0.57 ± 0.09	4.67 ± 1.15
	PD (n = 4)	0.52 ± 0.24	1.12 ± 0.52	0.48 ± 0.14	0.59 ± 0.22	6.67 ± 2.08
	p-value	0.8810	0.7888	0.3619	0.9910	0.3170
End Season 1	Test (n = 4)	0.43 ± 0.28	0.79 ± 0.47	0.30 ± 0.08	0.56 ± 0.33	4.00 ± 0.82
	IF (n = 4)	0.43 ± 0.25	0.77 ± 0.43	0.31 ± 0.14	0.57 ± 0.27	3.75 ± 1.50
	PD (n = 4)	0.45 ± 0.24	0.79 ± 0.42	0.34 ± 0.10	0.48 ± 0.21	5.25 ± 1.26
	p-value	0.9748 ^{W}	0.9961	0.8370	0.8762	0.2326
End Season 2	Test (n = 4)	0.39 ± 0.27	0.65 ± 0.40	0.30 ± 0.17	0.57 ± 0.26	3.50 ± 1.29
	IF (n = 4)	0.34 ± 0.27	0.54 ± 0.37	0.28 ± 0,22	0.57 ± 0.36	3.25 ± 1.89
	PD (n = 4)	0.23 ± 0.18	0.43 ± 0.30	0.34 ± 0.08	0.26 ± 0.17	5.00 ± 0.82
	p-value	0.6609	0.6946	0.8924	0.2259	0.2174
End Season 3	Test (n = 4)	0.18 ± 0.30	0.31 ± 0.49	0.15 ± 0.13	0.38 ± 0.49	2.25 ± 0.96
	IF (n = 4)	0.06 ± 0.06	0.14 ± 0.13	0.11 ± 0.09	0.22 ± 0.06	2.00 ± 0.82
	PD (n = 4)	0.26 ± 0.14	0.46 ± 0.23	0.20 ± 0.08	0.38 ± 0.15	3.25 ± 0.96
	p-value	0.3141 ^{W}	0.3413 ^{W}	0.4687	0.4474 ^{Z}	0.1724

Inorganic fertilization (IF); tomato plant debris (PD); no fertilization (Test). N° of Genera: number of genera. Different letters between columns and sampling indicate significant differences. ($p \leq 0.05$, Tukey's HDS test), ^{W}: $\frac{1}{log(x)}$, ^{Z}: $\sqrt{x}$;).

PERMANOVA analysis revealed differences in the composition of the cultivable fungal community as a function of the treatments applied (test, IF, and PD) at the end of the cultivation of the first two years of the trial (Table S1) where the experimental plots that received tomato plant debris (PD) showed a different fungal composition than inorganic fertilization (IF) and no fertilization (Test).

3.2.3. Fusarium Fungi

Figure 4 shows the results regarding culturable filamentous fungi of the genus *Fusarium* during the three campaigns. These results corroborate the findings for the general cultivable bacterial and fungal microbiota.

Generally speaking, soil solarization performed before the start of cultivation had a depressive effect on filamentous fungi of the genus *Fusarium* for the three treatments, which made them undetectable in the soil by the analytical technique used, regardless of the treatment (Figure 4). In the third year of the study, the soil that had received tomato plant debris showed values close to the initial ones. In any case, a tendency to reconstitute was detected at the end of the crop, especially in the soil that received tomato plant debris. Thus, at the end of the trial, the population density was higher than those of the other treatments with values close to the initial ones.

A total of four different species belonging to the genus *Fusarium* (*F. oxysporum*, *F. solani*, *F. equiseti*, and *F. proliferatum*) were identified by their morphology (Figure 5). Only *F. oxysporum* and *F. equiseti* species were identified in the soil of the plots that did not receive fertilization (test), while in the soil with inorganic fertilization (IF) and with tomato plant debris (PD) *F. solani* and *F. proliferatum* were also isolated. In general, when *Fusar-*

ium spp. were present, *F. oxysporum* was always the species with the highest expression, accounting for 74.9% of the total CFU counted.

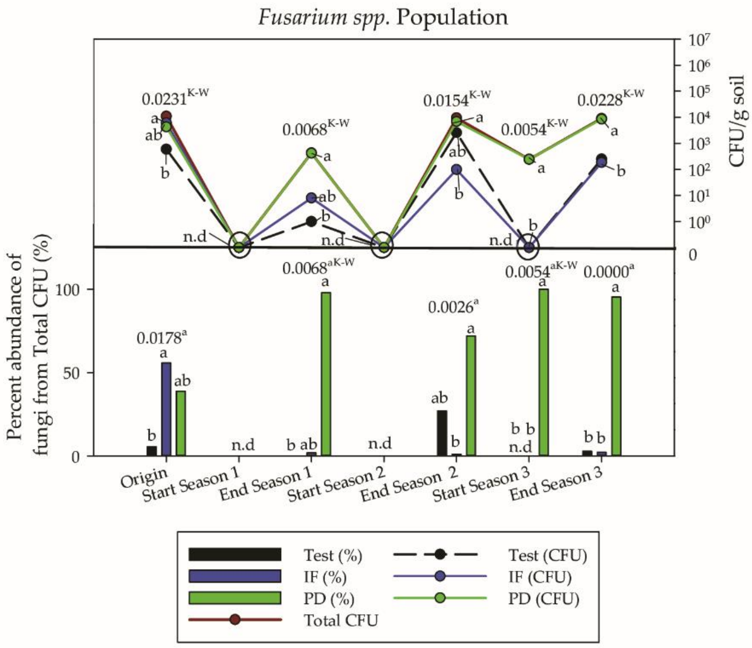


Figure 4. Soil *Fusarium* microbiota in the three years of study (September–April cycles) as a function of crop nutrition. Inorganic fertilization (IF; n = 4); tomato plant debris (PD; n = 4); no fertilization (Test; n = 4). N.d: not detected. Values (average). Different letters above the bars and in the evolution lines indicate significant differences. ($p \leq 0.05$, Tukey's HDS test), ^{a}: $arcsen\left(\sqrt{x}\right)$; $^{K\text{-}W}$: test Kruskal–Wallis test.

3.3. Physical and Chemical Variables of Soil Samples

The sand and clay contents maintained a constant trend during the trial with no influence of the treatment applied on these parameters (Figure S1). The addition of tomato plant debris increased the silt content and decreased the hydraulic conductivity of the soil compared to inorganic fertilization (Figure 6).

Carbonate, assimilable phosphorus, C/N ratio, E.C., and limestone contents were not influenced by the fertilization plan applied during the experiment (Figure 6 and Figure S1). However, each of the treatments increased the E.C. of the soil. In addition, the experimental plots where tomato plant debris was applied showed the highest limestone concentration and an increase in the C/N ratio was observed after solarization. Soil pH was significantly increased by the addition of tomato plant debris compared to inorganic fertilization. At the end of the trial, SOM values were higher in soil that received vegetables during the three years of study while detecting an increase of 3.8% with respect to the initial value, while IF registered a decrease of 14.9%.

In the three years of the study, assimilable potassium values increased after the addition of tomato plant debris and solarization, while they decreased at the end of the crop (Figure 6). In the case of the IF treatment, the trend is the opposite. At the beginning of the crop, the assimilable potassium content was always higher in the plots that received tomato plant debris compared to the rest of the treatments.

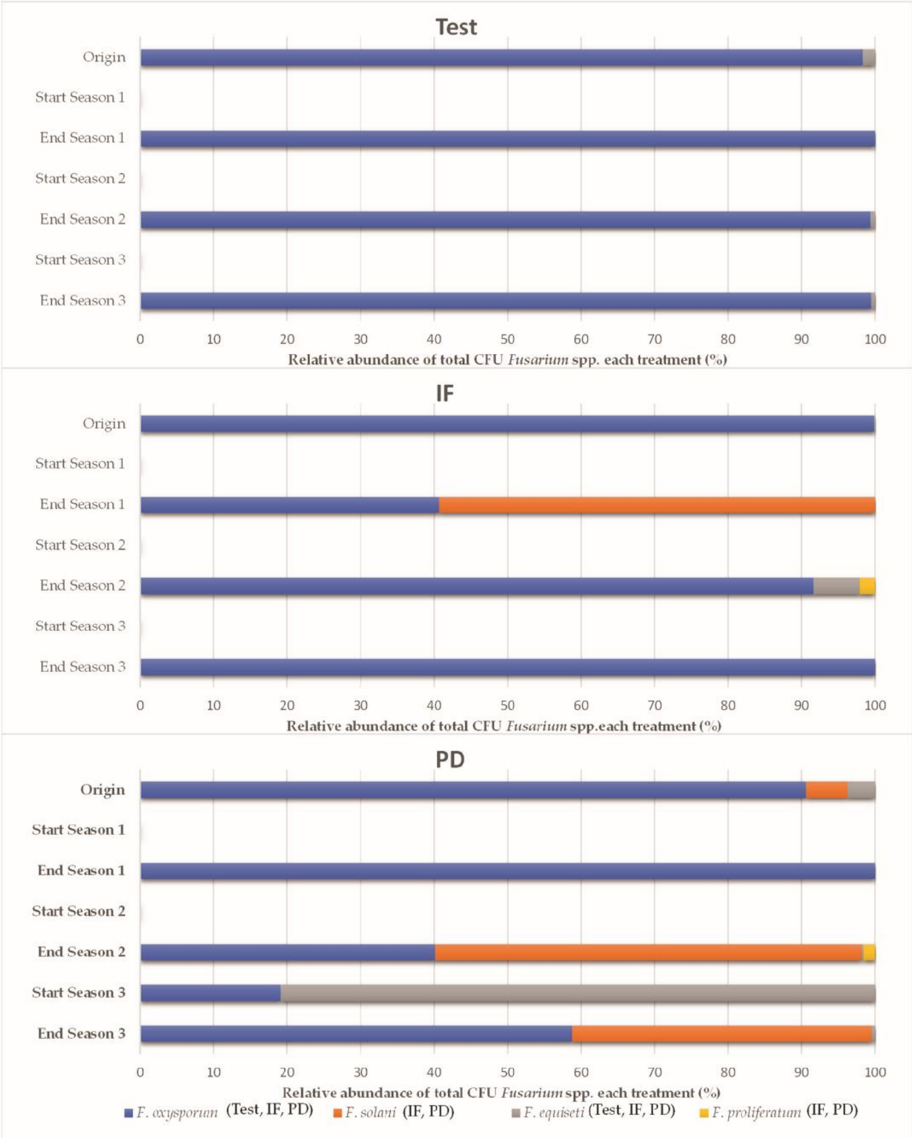


Figure 5. Relative abundance of *Fusarium* species in the three years of study (September–April cycles) as a function of crop nutrition. Inorganic fertilization (IF; n = 4); tomato plant debris (PD; n = 4); no fertilization (test; n = 4). Values (average).

3.4. Plant Growth in a Controlled Environmental Chamber

This research aimed to evaluate the modifications found in solarized soil with or without tomato plant debris. The model used enabled the evaluation of vigor expression in tomato and cucumber seedlings. The tests suggest that the addition of plant debris with solarization produced a greater expression of seedling vigor (number of leaves, height, aerial dry weight, root dry weight and leaf area) (Figure 7 and Figures S2 and S3). This expression was most visible in the leaf area, thus corroborating the results obtained in the greenhouse.

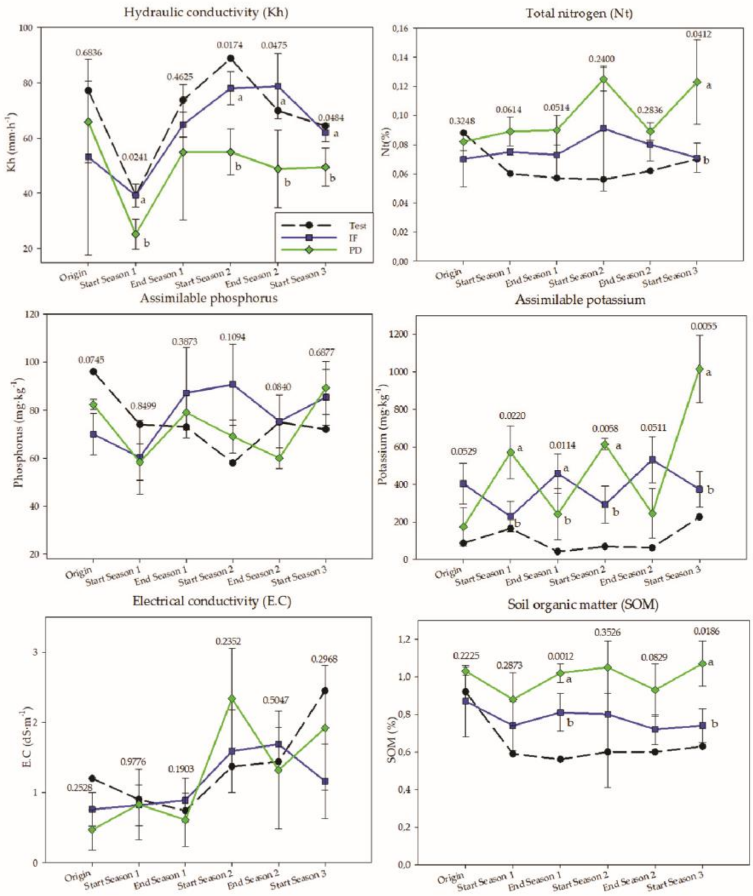


Figure 6. Soil physicochemical parameters in the three years of study (September–April cycles) as a function of crop nutrition. Inorganic fertilization (IF; n = 3); tomato plant debris (PD; n = 3); no fertilization (test; n = 1). Values (mean ± standard deviation). Different letters indicate significant differences between IF and PD ($p \leq 0.05$, Student's *t*-test).

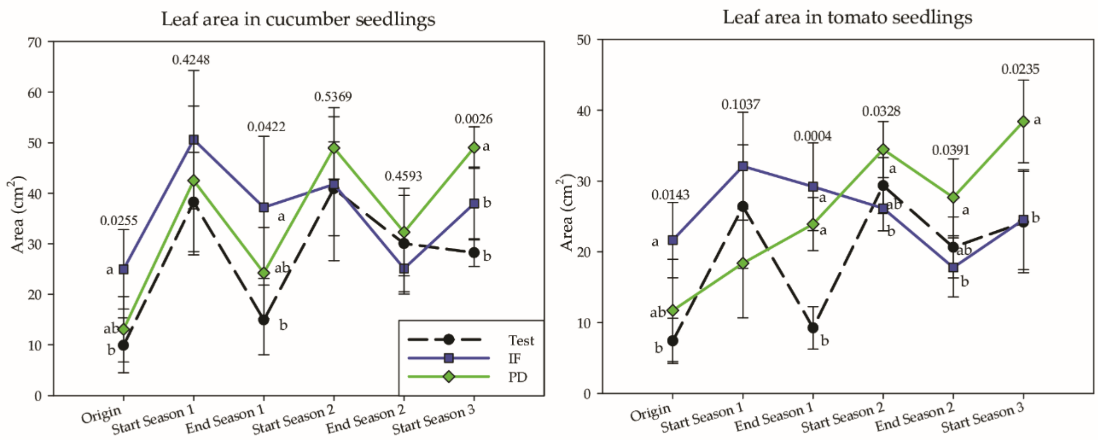
3.4.1. Tomato

The application of the three treatments did not show a homogeneous behavior among the plant vigor variables measured (Figure 7 and Figure S2). However, the repeated addition of tomato plant debris progressively increased the leaf area of tomato seedlings, while inorganic fertilization showed an inverse trend. At the end of the trial, the PD treatment showed a statistically higher aerial dry weight and leaf area than test and IF. Root dry weight increased at the end of each year's production cycle in all three treatments.

3.4.2. Cucumber

The vigor variables measured on cucumber seedlings showed a lower sensitivity to the effect of the applied treatments (Figure 7 and Figure S3). At the end of the trial, the addition of tomato plant debris statistically differentiated the leaf area of cucumber seedlings compared to inorganic fertilization and no fertilization. The leaf area of cucumber seedlings increased on average after solarization for all three treatments regardless of whether or not tomato plant debris was applied. Non-fertilization had a negative influence on the seedling height at the end of the experiment.

The stepwise linear regression analysis showed a variable response to the prediction of the independent variables (vigor parameters) of both vegetable species (tomato and cucumber) (R^2: 0.106–0.343) (Table S2). However, the predictive models coincided in reporting C/N ratio and carbonate concentration in both vegetable species as factors that manifested a direct and inversely proportional relationship in the prognosis of some of the vigor parameters (number of leaves, height, root dry weight, and leaf area).



(**a**) (**b**)

Figure 7. Leaf area of seedlings grown in controlled chamber conditions in the three years of study (September–April cycles) as a function of crop nutrition: (**a**): cucumber; (**b**): tomato. Inorganic fertilization (IF; n = 4); tomato plant debris (PD; n = 4); no fertilization (Test; n = 4). Values (mean ± standard deviation). Different letters in the evolution lines indicate significant differences ($p \leq 0.05$, Tukey's HDS test).

4. Discussion

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. 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 [61–66] to obtain a tomato fruit of similar quality [62–64]. 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 [35–38,67]. It should also be noted that the soil biosolarization technique can have an influence on soil fertility [28–32,68] 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 [20,69]. 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 [61]. However, some authors did not obtain differentiated production between their treatments fertilized only with organic amendments and the absence of fertilization [69].

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. 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 [60,70,71], although in some, there was no repetition of the solarization technique over time [60]. 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. [60]. 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 [72]. 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 [24,60,70] 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 [71]. 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 [73]. 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.) [74–76], participate in nitrification processes (*Aspergillus* spp., *Penicillium* spp.) [77], promote plant growth (*Trichoderma* spp.) [78] or practice saprophytism (*Aspergillus* spp., *Penicillium* spp., *Trichoderma* spp.) [79,80]. 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 [78].

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. [68] 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 [24,29,81]. 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 [41,82]. 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. [83] 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.

5. 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.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph182111544/s1, Figure S1: soil physicochemical parameters in the three years of study (September–April cycles) as a function of crop nutrition, Figure S2: number of leaves, height and root and aerial dry weight of cucumber seedlings grown in controlled chamber conditions in the three years of study (September–April cycles) as a function of crop nutrition, Figure S3: number of leaves, height and root and aerial dry weight of tomato seedlings grown in controlled chamber conditions in the three years of study (September–April cycles) as a function of crop nutrition, Table S1: PERMANOVA analysis of the fungal community in the three years of study (September–April cycles) as a function of crop nutrition, Table S2: stepwise linear regression models evaluating the prediction of growth variables of tomato and cucumber seedlings grown in controlled chamber conditions.

Author Contributions: Conceptualization, F.J.C.-D., J.I.M.-G., L.J.B.-U. and J.C.T.-M.; data curation, F.J.C.-D., J.I.M.-G., L.J.B.-U. and J.C.T.-M.; formal analysis, F.J.C.-D., J.I.M.-G., L.J.B.-U. and J.C.T.-M.; funding acquisition, F.J.C.-D. and J.C.T.-M.; investigation, F.J.C.-D., J.I.M.-G., L.J.B.-U. and J.C.T.-M.; methodology, F.J.C.-D., J.I.M.-G., L.J.B.-U. and J.C.T.-M.; project administration, J.C.T.-M.; resources, J.C.T.-M.; software, F.J.C.-D. and J.I.M.-G.; supervision, J.I.M.-G., L.J.B.-U. and J.C.T.-M.; validation, J.I.M.-G., L.J.B.-U. and J.C.T.-M.; visualization, J.I.M.-G., L.J.B.-U. and J.C.T.-M.; writing—original draft, F.J.C.-D. and J.I.M.-G.; writing—review and editing, F.J.C.-D., J.I.M.-G., L.J.B.-U. and J.C.T.-M. All authors have read and agreed to the published version of the manuscript.

Funding: The present research has not received any funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors wish to thank the dedication of the members of the AGR-200 Research Group of the University of Almeria, especially César Antonio Ruiz Olmos, and the UAL-ANECOOP Experimental Farm.

Conflicts of Interest: The authors declare no conflict of interest.

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CAPÍTULO III: BIODISINFECTION AS A PROFITABLE FERTILIZATION METHOD FOR HORTICULTURAL CROPS IN THE FRAMEWORK OF THE CIRCULAR ECONOMY

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Biodisinfection as a Profitable Fertilization Method for Horticultural Crops in the Framework of the Circular Economy

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Abstract: Intensive agriculture has resulted in various environmental impacts that affect ecosystems. In some cases, the application of conventional fertilizers has deteriorated water quality, which includes the marine environment. For this reason, institutions have designed various strategies based on the principles of the circular economy and the bioeconomy. Both of these dynamics aim to reduce excessive fertilization and to inhibit the negative externalities it generates. In our work, a field trial is presented in which a 100% reduction in conventional inorganic fertilizers has been evaluated through a production methodology based on fertilization with reused plant debris in combination with other organic compounds. Based on one tomato crop, the profitability of this production technique has been analyzed in comparison with other conventional vegetable production techniques. The productivity and economic yield of the alternative crop was similar to that of the conventional crop, with a 37.2% decrease in water consumption. The reuse of biomass reduced production costs by 4.8%, while the addition of other organic amendments increased them by up to 22%. The results of our trial show that farms are more sustainable and more profitable from a circular point of view when using these strategies.

Keywords: circular economy; agricultural waste management; cost–benefit analysis; sustainable agriculture; alternative crops

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Citation: Castillo-Díaz, F.J.; Belmonte-Ureña, L.J.; Camacho-Ferre, F.; Tello Marquina, J.C. Biodisinfection as a Profitable Fertilization Method for Horticultural Crops in the Framework of the Circular Economy. *Agronomy* **2022**, *12*, 521. https://doi.org/10.3390/agronomy12020521

Academic Editor: David Houben

Received: 1 January 2022
Accepted: 17 February 2022
Published: 19 February 2022

1. Introduction

In the last sixty years, the socio-economic structure of the province of Almeria (Spain) has undergone a metamorphosis due to the development of high-yield agriculture based on the greenhouse production of eight fruit and vegetable species (tomato, bell pepper, watermelon, zucchini, cucumber, watermelon, melon, eggplant, and green bean) [1]. The production model is at a stage of productive maturity [2]. The value at origin of the merchandise was estimated at EUR 2.3 million in the 2020/2021 campaign [3]. However, the economic benefit for farmers in Almeria has diminished in recent years, even to the point of economic losses in some of the crop rotations traditionally used [2]. Production costs have increased while the price at origin of fruits and vegetables has remained constant. In addition, there has been competition with developing countries that produce their goods at lower costs mainly because they spend less on labor [2,4].

From an environmental point of view, the Almeria model employs a production methodology that uses less energy than other similar agricultural systems. The most widespread production structure is the unheated "Raspa y Amagado" greenhouse [5–7]. In addition, various agro-ecological techniques are generally used during the production of fruit and vegetable products (e.g., integrated production, biological control, bio-disinfection, etc.) [3,8]. However, Almeria's natural landscape has also suffered from different environmental impacts due to agricultural production, leading to a loss of biodiversity, soil erosion, overexploitation of aquifers, and the accumulation of agricultural waste in the natural environment, among others [9–11].

At the end of the 20th century, the dumping of agricultural waste in the natural environment of Almeria provoked a health crisis. The ecosystems were polluted with crop residues mixed with the polypropylene ropes used in plant trellising. The situation led to an intervention by public institutions to correct the problems generated. As a result, various actions have been carried out to rid the countryside of Almeria of agricultural residues [11–13].

Recently, the European Union has developed different strategies and regulations that try to improve sustainability in the production model. They are based on the principles of the bioeconomy and circular economy [14–16]. The aim is to obtain economic growth that is decoupled from natural resource consumption and net greenhouse gas emissions by 2050 [16]. This calls for profound change in the production structure of the European Union through the use of new and environmentally friendly production methods since more than half of the world's GDP depends on nature and its biodiversity [14,17]. Furthermore, these production methodologies must be designed in such a way as to allow for the reuse, reduction, and recycling of the inputs used [15]. Two documents mainly concern agriculture—the farm-to-fork strategy and the biodiversity strategy. Regarding the agricultural process, there is a need to reduce the following: nutrient losses by 50% (mainly nitrogen and phosphorus), the application of fertilizers by 20%, and the use of phytosanitary products by 50%. There is also a call to increase the area under organic certification by 25% [18]. In terms of waste, there is a need to reuse the secondary elements (by-products) obtained in the production processes [19]. For this reason, the identification of alternative production methods that provide producers with the tools they need to meet these objectives is of great interest.

In Almeria, around 1.8 million tons of vegetable waste is generated annually. Most of this material is managed by an external manager who converts the material into compost at a cost assumed by the farmers [12]. However, this management system does not offer a complete solution for the needs of the agricultural sector in Almeria, and this has led to the dumping of agricultural biomass into the natural areas of the territory [11]. The main reason for this is the seasonal production of more than 80% of plant debris in only three months (February, May, and June), which makes it difficult to maintain stable inputs for the transformation processes of the vegetal element [12,20]. In addition, in some agricultural districts, the low number of farms does not justify the investment to build management plants, which increases transport costs and makes it more difficult to manage the agricultural biomass [12]. Some of the alternatives evaluated have not been able to mitigate the problems generated (i.e., energy production, animal feed, etc.), mainly due to the low caloric content of plant debris compared to other by-products or the seasonal production [20].

There are several opportunities to apply the principles of the bioeconomy and circular economy in the Almeria model [11,21,22], which has been identified as one of the collective changes to be made in the production system [10]. The reuse of plant debris can help to reduce the quantity of inorganic fertilizer applied to crops, mainly when their incorporation is carried out through the biosolarization technique [23–25] to decrease production costs [11]. However, the self-management of plant residue is not a technique that is widespread in greenhouse agriculture in Almeria [5].

The biosolarization technique is a bio-disinfection methodology that combines soil solarization and biofumigation [26,27]. It has been traditionally used as an alternative to chemical soil disinfectants because of its effectiveness in pathogen control [28–34]. In addition, benefits to soil fertility have also been observed during its use due to the improvement of physical (infiltration rate) [23,35] and chemical (organic matter content, total nitrogen, available potassium, available phosphorus, etc.) properties [23,34,36–38]. This has resulted in significant increases in the production of horticultural crops grown in soils free of previous edaphic diseases [36]. Some of the organic amendments that have been traditionally used are plants of the *Brassica* genus. Specifically, they have been used both as a kind of green manure [39] or in the form of transformed compounds presented as dehydrated pellets [30,40]. They have been attributed an ability to limit the development of soil pathogens and, thus, the capacity to infest plants through the synergistic effect produced between the ascensus of soil temperature [26] and compounds obtained from the decomposition of organic amendments such as glucosinolates [39]. However, other organic amendments, such as plant debris or manure, have shown a similar effect in terms of disease control [29–31]. In addition, the fertilizing effect of organic amendments has rarely been tested in previous research, as crops have been managed under commercial practices and inorganic fertilizers have been added. The use of by-products (i.e., agricultural biomass) in biodisinfection techniques can reduce external dependence on inputs and promote their management through a circular approach [24].

The sustainability objectives set by the European Union proposed a paradigm shift in its production structure, which affects crop fertilization. Therefore, the problem is more serious when dealing with intensive agriculture that uses a high amount of inorganic fertilizers. Previous research has proposed plant debris or manure with solarization in soils free of edaphic pathologies as an alternative to the fertilizer reduction proposed by the European Union [23,41]. However, the existing information is not abundant when these organic amendments are combined with *Brassica carinata* pellets in disease-free soils in long production cycles. Moreover, they are not accompanied by economic balance. Thus, the objectives of this research were the following:

- To evaluate the fertilizing effect of various organic amendments (*Brassica carinata* pellets and/or tomato plant debris) on final production and quality with a 100% reduction in inorganic fertilization versus conventional cultivation and no fertilization in tomato production cycles of at least seven and a half months, the vigor of seedlings grown under controlled conditions, the application of irrigation water, and the economic benefit.
- To study the economic impact of the reuse of plant debris on the economic benefit of the five main rotation alternatives used in greenhouse agriculture in the province of Almeria.

2. Materials and Methods

2.1. Location, Greenhouse, Irrigation System, and Soil

The experiment was carried out over three consecutive years (2015–2016, 2016–2017, and 2017–2018) at the experimental farm "Catedrático Eduardo Fernández" of the UAL-ANECOOP Foundation, located in the municipality of Almeria (Spain). The greenhouse used was the "Raspa y Amagado" type, a typical production structure of the Almeria model [7] with an area of 1784 m^2 and a northwest–southwest orientation. The crop rows were double and had a similar orientation. The heights of the ridge and lateral bands were 4.70 and 3.40 m, respectively. The greenhouse irrigation system consisted of two independent sectors, which allowed for the supply of different water and inorganic fertilizers to each sector. The emitters provided a nominal flow rate of 3 $L \cdot h^{-1}$. The greenhouse soil was a mixture of gully soil and sand. The soil texture was sandy loam, and its physicochemical composition is shown in Table 1.

Table 1. Physical and chemical composition of greenhouse soil.

	Variables
Initial analysis	Sand: 76.0 ± 4.1%; slime: 7.0 ± 0.8%; clay: 8.8 ± 6.2%; pH: 7.80 ± 0.22; SOM: 0.93 ± 0.14%; C/N: 7.0 ± 0.8; active limestone: 3.9 ± 1.5%; carbonates: 26.8 ± 3.1%; N: 0.078 ± 0.014%; P: 79.00 ± 10.98 $mg \cdot kg^{-1}$; K: 259.29 ± 162.08 $mg \cdot kg^{-1}$

Source: own elaboration based on Castillo-Díaz et al. [23].

2.2. Production Cycles and Crop Management

The tomato production cycles began with the transplanting of the seedlings during the first week of September in each year of the trial and lasted 215, 212, and 217 days after transplanting (DAT), respectively, while extending until April of the following year. In each year of the experiment, tomato (*Solanum lycopersicum* Mill.) cultivar "Pitenza F1" (Enza Zaden, Enkhuizen, The Netherlands) seedlings that had been grown in the seedbed for approximately 35 days were used. The initial planting density was 2 plants/m^2. The tomato crop received the cultural management suggested by Camacho-Ferre [42]. Tomato plants were guided through polypropylene ropes (raffia) without using staking clips. On-demand irrigation was applied to each sector of the greenhouse based on readings taken from two IRROMETER Model R tensiometers (Irrometer, Riverside, CA, USA). Pests and diseases were controlled according to Integrated Production (IP) regulations.

2.3. Experimental Design

A single-factorial experimental design with four experimental plots for each treatment (n = 4) was used in this trial. The treatments used in the investigation depended on the main source of nutrition applied (i.e., organic, inorganic, or non-fertilization). Thus, the treatments that received inorganic nutrition were located in a different sector of the greenhouse from those that were fertilized only with organic amendments or those that were not fertilized to avoid cross-contamination between experimental plots. The experimental design used was the one previously published by Castillo-Díaz et al. [23], with the addition of four more treatments for each year of the trial. During the first two years, exclusive fertilization with 3.5 kg·m^{-2} tomato plant debris and inorganic fertilization were combined with *Brasssica carinata* pellets (BioFence®) at doses of 0.5 y 1.0 kg·m^{-2}. The dose recommended by the manufacturer (0.3 kg·m^{-2}) was increased based on the results obtained in two previous investigations [24,36]. In the third year of the trial, the addition of *Brasssica carinata* pellets in both the organic and inorganic fertilization was eliminated and replaced by various doses of tomato plant debris. The treatments used during the three years of the trial are shown in Table 2.

Table 2. Treatments applied to the greenhouse tomato crop during the research (September–April cycles).

	Code	Block	Treatment
Crops 1 and 2	Test *	-	Without fertilization
	IF *	IF	Inorganic fertilization
	IFB1		Inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets
	IFB2		Inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets
	PD *	PD	3.5 kg·m^{-2} of tomato plant debris
	PDB1		3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets
	PDB2		3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets
Crop 3	Test *	-	Without fertilization
	IF *	IF	Inorganic fertilization
	IFPD		Inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris
	IFPD1		Inorganic fertilization + 5.0 kg·m^{-2} of tomato plant debris
	PD *	PD	3.5 kg·m^{-2} of tomato plant debris
	PD1		5.0 kg·m^{-2} of tomato plant debris
	PD2		6.5 kg·m^{-2} of tomato plant debris

* Source: own elaboration based on Castillo-Díaz et al. [23].

2.4. Disinfection Process

In each of the three years of the trial, physical soil disinfection (solarization) or biosolarization (solarization + organic amendments) procedures were applied before transplanting the tomato seedlings. The procedure began with the elimination of the trellising raffia from the previous tomato plant crops. Subsequently, the plant debris was deposited on the central concrete aisle of the greenhouse. Afterward, the drip branches were collected and the tomato plant debris was shredded using a hammer mill. The shredded material was spread on the soil surface of the experimental plots using the element in the doses tested (Table 2). The tomato plant debris was then mixed into the upper soil profile (at a depth of 20–30 cm) using a rotovator. During the first years of the trial, furrows were opened in treatments IFB1, IFB2, PDB1, and PDB2, and the tested doses of *Brassica carinata* pellets were added. The furrows were then closed after the addition of the material. The experimental plots of the Test and IF treatments did not receive any additional tomato plant debris or *Brassica carinata* pellets during the three years of investigation.

After the incorporation of the organic amendments, the drip lines were reinstalled and the floor of the entire greenhouse was covered with a transparent polyethylene cover with a thickness of 50 μm (except for the central concrete aisle). The contour of the plastic cover was sealed while employing a groove (20 cm base and 30 cm height), and the polyethylene sheets were joined together using staples and it was attached to the different posts of the greenhouse with adhesive tape. Finally, irrigation was applied until the soil reached the saturation point (56 $L \cdot m^{-2} \cdot year^{-1}$). The duration of the disinfection treatments was three months each year, and they were carried out between June and September.

The experimental plots for all treatments used during the three years of research had an area of 40 m^2 (80 tomato plants per repetition), except for the Test treatment, which was assigned half the area and number of plants.

2.5. Crop Production

The crop yield was evaluated during the 14, 15, and 18 harvests carried out in the three crop cycles, respectively. Operations started from 92 DAT of the first crop, and from 99 DAT on the second and third crops. The criterion for commercial maturity was dictated by the marketing entity during the three crop cycles. The variables calculated were the cumulative production per unit area and the fruit mass. For this purpose, the products obtained from each experimental plot were quantified independently. In addition, 25 tomato fruits were randomly selected from each repetition and their masses were determined. The measurements were made with a scale (Mettler Toledo®, Columbus, OH, USA) with a sensitivity of 0.01 g.

2.6. Crop Quality

The tomato fruit quality was assessed five times during each production cycle, and the measurements ranged from 106 to 217 DAT. On the days of analysis, 10 tomato fruits per replicate were selected. A total of 200 fruits were analyzed for each treatment and year. Four parameters were analyzed—the equatorial diameter of the fruits by means of a digital caliper with a sensitivity of 0.01 mm (Mitutoyo; Kanagawa, Japan); the average firmness of the fruit pulp using a hardness tester with a sensitivity of 0.001 $kg \cdot cm^{-2}$ (Penefel DFT14, Agrosta, Compainville, France) found from three points located on the equatorial diameter of the fruit and equidistant from each other; the total soluble solid content in the fruit pulp with a refractometer with a sensitivity of 0.1 °brix, and the pH in the fruit pulp with a pH meter with a sensitivity of 0.01 pH units (pH-25, Crison, Barcelona, Spain).

2.7. Evaluation of Seedling Growth in a Controlled Environment Chamber

1. Sampling and soil samples

Six different samplings were carried out during the research. The first was taken prior to the soil disinfection procedure (solarization or biosolarization) performed before the first crop. The remaining samples were taken at a rate of two per year, one immediately after soil disinfection (first week of September) and another after the end of cultivation (second week of April).

Soil samples were collected from three equidistant points located at an average distance between the two crop rows of each experimental unit. The masses of the samples were approximately 10 kg. After collection, they were homogenized and stored in a transparent polyethylene bag at 8 °C until analysis. The soil samples from the end of the third crop could not be analyzed due to a preservation problem.

2. Definition and plant material

The research included trials carried out with the horticultural seedlings of cucumbers (*Cucumis sativus cv.* Marketmore 76; Ramiro Arnedo S.A, Calahorra, Spain) and tomatoes (*Solanum lycopersicum* L. *cv.* Río Grande; Ramiro Arnedo S.A., Calahorra, Spain) grown in a controlled environment to observe the effect of the treatments applied on several variables regarding plant vigor. In other studies, this methodology has been proven to be more sensitive in expressing the fertility associated with soil samples [23,43–46].

3. Description of the experiments

The experiments were performed in a controlled environment with a photoperiod of 14 h of daylight per day and a temperature of 21–25 °C. The lamps used were low-pressure mercury vapor lamps with a luminous flux of 12,000 lm. The horticultural species (cucumber and tomato) were planted in pots with a volume of 200 cm^3. A substrate formed by soil and vermiculite at a 2:1 v/v ratio was poured into the pots, which included one seed each (experimental unit). Five replicates were carried out for each plant species and soil sample (20 pots per treatment and vegetable species). The seeds were disinfected with a 20% solution of sodium hypochlorite (40 $g \cdot L^{-1}$) for 15 min and rinsed with water from the municipal water supply. The trials lasted 30 days. During this time, on-demand irrigation was applied and no fertilizer was used. The experiment was conducted twice for each soil sample collected.

4. Analyzed variables and measurement process

Five plant vigor variables were measured for each cucumber and tomato seedling, as they were the most representative parameters in previous studies. The variables were the number of leaves, seedling height, aerial dry mass, root dry mass, and leaf area. After having carefully removed the dirt adhered to the horticultural seedlings with water from the municipal water supply, they were divided into two portions—the aerial part and the subway part—before being placed on filter paper. A dehydration protocol was then applied for 48 h at 72 °C with a J.P-Selecta Dry-Big 2003720 (Barcelona, Spain) until the mass of the seedlings acquired a constant value. The aerial and root masses were measured with a Metter Toledo PB 303-S balance (Columbus, OH, USA) with a sensitivity of 0.001 g. The numbers of leaves and heights were quantified visually at the beginning of the dehydration treatment, also using a tape measure with a sensitivity of 0.1 cm. The leaf area was determined with the free software ImageJ 1.48 (NIH Imagen, Bethesda, Maryland) after scanning the leaves and leaflets of the seedlings with an Epson Perfection 1240 optical reader (Epson, Suwa, Japan).

2.8. Irrigation Water

In the third year of the trial, an estimation of the water applied to each irrigation sector (i.e., IF block and PD block) was made. The measure was obtained from the frequency, irrigation time, and flow rate applied to each irrigation sector.

2.9. Economic Analysis

Two economic analyses were carried out, which were based on the principle of maximizing the benefit to the farmers. According to the experimental results of this study, a proposal was made to reduce costs by cutting down on various agricultural inputs (i.e., water, fertilizers, chemical disinfectants, and sanding management). The profit before tax (NPbt) was used as a determinant parameter. The variable was calculated using the following mathematical expression:

$$\text{NPbt} = \text{TNR} - \text{TC}, \tag{1}$$

NPbt—profit before tax; TNR—total annual revenues; TC—total cost.

2.9.1. Analysis 1

The annual pre-tax economic benefit obtained by the 11 treatments applied in the experimental greenhouse was studied (Table 2). The technical characteristics of the greenhouse used and the production methodology are those shown in Sections 2.1 and 2.2, respectively.

2.9.2. Analysis 2

The pre-tax economic benefit of the five horticultural alternatives suggested by Honoré et al. [2] was evaluated. However, the study period was extended to five consecutive years spanning February 2016 to January 2021 (Table 3). The species used in the different alternatives are those commonly used in greenhouse agriculture in Almeria (four cucurbits, three solanaceous, and one legume) [1,8]. The first four alternatives employ a production methodology based on short crop cycles (i.e., two cycles per year—autumn to winter cycle + spring to summer cycle).

Table 3. Crop alternatives economically evaluated in the 2016–2021 period.

Alternatives	Series of Crops
1	Watermelon (2016) [2] + tomato (2016) [1] + zucchini (2017) [2] + pepper (2017) [1] + watermelon (2018) [2] + tomato (2018) [1] + zucchini (2019) [2] + pepper (2019) [1] + watermelon (2020) [2] + tomato (2020) [1]
2	Tomato (2016) [2] + cucumber (2016) [1] + eggplant (2017) [2] + green bean (2017) [1] + melon (2018) [2] + tomato (2018) [1] + cucumber (2019) [2] + eggplant (2019) [1] + melon (2020) [2] + green bean (2020) [1]
3	Melon (2016) [2] + pepper (2016) [1] + watermelon (2017) [2] + tomato (2017) [1] + melon (2018) [2] + pepper (2018) [1] + watermelon (2019) [2] + tomato (2019) [1] + melon (2020) [2] + pepper (2020) [1]
4	Zucchini (2016) [2] + eggplant (2016) [1] + melon (2017) [2] + pepper (2017) [1] + watermelon (2018) [2] + eggplant (2018) [1] + zucchini (2019) [2] + pepper (2019) [1] + melon (2020) [2] + eggplant (2020) [1]
5	Zucchini (2016) [2] + tomato (2016–2017) [3] + tomato (2017–2018) [3] + tomato (2018) [1] + watermelon (2019) [2] + tomato (2019–2020) [3] + tomato (2020) [1]

[1] Autumn–winter cycle; [2] spring–summer cycle; [3] single cycle. Source: own elaboration.

- Production methodologies evaluated in Analysis 2

The estimated duration of the vegetative development phase and productive period for each season was 310 DAT. A total of 55 days were considered for the other pre-and post-cultivation tasks. The five horticultural alternatives were subjected to three production methodologies, as follows:

- Methodology 1: The conventional production protocol performed in the greenhouse horticultural field of Almeria as described by Honoré et al. [2].
- Methodology 2: An alternative production model. A proposal for the self-management of plant debris obtained during the production process. A reduction in the water (37.2%), land preparation, external management of plant debris (100%), and chemical soil disinfectants (100%) is contemplated. However, traditional inorganic cover crop fertilization is maintained.

In this methodology, a single addition of all the plant debris obtained during the entire campaign is applied in the summer months before the beginning of the following campaign. The amount of vegetable debris added was 5 kg·m^{-2} of fresh matter. A biosolarization protocol was applied after their incorporation. For the short-cycle horticultural alternatives, the vegetable debris obtained from the autumn–winter cycle are stored at the farm under a thermal blanket.

- Methodology 3: Production Methodology 2 is carried out contemplating a total reduction in inorganic fertilizers during 215 of the 310 days of the vegetative growth phase and the production period.

2.9.3. Income and Expense Structure

The income and expense structure used in this work was based on the one proposed by Honoré et al. [2], which followed the guide used by the experimental farm "Catedrático Eduardo Fernández" of the UAL-ANECOOP Foundation and the one suggested by Toresano and Ca-macho-Ferre [47] for Agroseguros, S.A.-Spain. The latter corresponded to unpublished data obtained as a result of Service Provision PS20120000000000184 of the Research Results Office (OTRI) of the University of Almeria. The values provided have been updated annually under the general national index ECOICOP (European Classification of Individual Consumption by Purpose).

1. Cost

Regarding the variable operating costs, it was estimated that the price of soil preparation is similar for all the types of crops studied. Land preparation was adjusted to the duration of the production cycles (short or long cycles). In addition, the costs of conventional soil disinfection were incorporated, as they were not included in the "land preparation" item [2]. Biennial solarization disinfection and quadrennial chemical disinfection were estimated for Analysis 2. As for Analysis 1, the item of land preparation was not considered since the greenhouse does not have a sanding system, and the disinfection expenditure was adjusted to the specific one obtained in the greenhouse. Seed and seedbed expenses were obtained by the annual cost for each plant species. The expenses for water, fertilizers, phytosanitary products, labor, tutors, auxiliary insects, and crop residue management were included under the heading "Growing and development until 1st inflorescence." "Flowering periods until 1st harvesting season" and "From the 1st harvesting season until the end of the cultivation" were included under the same heading ("Inputs and labor"), and the concepts water, fertilizers, and crop residue management were eliminated and incorporated as independent items. Water and fertilizer expenses for each species and season were obtained from the Price and Market Observatory of the Junta de Andalucia [48]. The water and fertilizer expenses for each species and season were obtained from the Price and Market Observatory of the Junta de Andalucia [48]. The cost of plant residue management was obtained from the one reported by Torres-Nieto [49] (removal from the greenhouse + transport to the plant + management at the plant). In addition, a specific item was added ("Incorporation of plant debris") that includes the costs of the raffia removal, pre-treatment, shredding, incorporation into veneers, and, if it is necessary to conserve the shredded material, a thermal blanket. The prices of the thermal blanket, *Brassica carinata* pellets (BioFence®), and chemical disinfectant were obtained after consultation with centers supplying inputs to farms. The expenses for the cover and structure include the expenditure on accessory inputs for the greenhouse cover and auxiliary production structures.

As for fixed costs, depreciation and amortization were calculated for all the production methods used in each analysis. In addition, all the expenses for energy, insurance, and financial services were included.

2. Income

The income was obtained from the product between production and the price at origin of the fruit and vegetable species. In Analysis 1, the income was calculated from the cumulative production per unit area of each experimental plot and the average price of a tomato offered by the Observatory of Prices and Markets of the Junta de Andalucia in the harvest periods of the 2015/2016, 2016/2017, and 2017/2018 campaigns (i.e., between the months of December and April) [48]. In Analysis 2, it was obtained from the production per unit of the annual average area and the annual average price of each plant species. The annual average in the Almeria model was reported by the Government of Andalucia [2,48].

2.10. Statistical Treatment

A statistical treatment consisting of an analysis of variance (one-way ANOVA) was performed to study the general effect of the treatments applied to the soil (i.e., Test, IF, IFB1, IFB2; PD, PDB1, PDB2, IFPD, IFPD1, PD1, and PD2) on the different parameters evaluated (production, quality, plant vigor in a controlled environment chamber, and Economic Analysis 1). In addition, an independent statistical treatment that separately confronted the treatments included in the inorganic (IF, IFB1, IFB2, IFPD, IFPD1) and organic (PD, PDB1, PDB2, PD1, and PD2) blocks for each year of research was carried out. This analysis was performed to observe the influence of *Brassica carinata* pellets (BioFence®) and tomato plant debris, using the IF and PD treatments as controls, respectively.

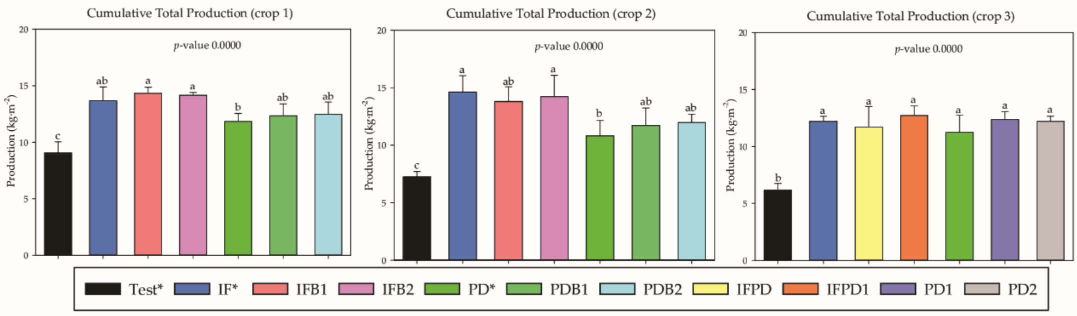
Beforehand, the assumptions of normality and homoscedasticity were verified with the Shapiro–Wilk and Bartlett tests, respectively. Subsequently, a multiple range test was performed using Tukey's honestly significant difference *post hoc* test (Tukey's HDS) at a confidence level of 95%. In the case of not meeting the requirements of the analysis of variance (one-way ANOVA), the nonparametric Kruskal–Wallis test was used. Statistical analyses were performed with STATGRAPHIC CENTURION XVIII statistical software (Manugistic Incorporate, Rockville, Maryland) for Windows.

3. Results and Discussion

This study was intended to provide a broader view of the effects on final commercial production and its quality using fresh tomato plant debris from the previous crop with or without *Brassica carinata* pellets incorporated through the biosolarization technique as a sole source of fertilization versus a conventional crop and no fertilization, as well as the vigor of seedlings grown under controlled conditions to monitor soil fertility, and an economic profitability analysis. Previous research has reported that fresh tomato plant debris can maintain a similar yield to that of the conventional crop in cycles of approximately 215 DAT [23]. The addition of *Brassica carinata* to fresh plant debris has been successful in maintaining yields similar to fresh plant debris in tomato production cycles with a duration of less than 170 DAT [24,50]. However, information is limited when it comes to long-duration cycles. Additionally, it is complemented with an economic analysis of five crop alternatives traditionally used in the Almeria model to observe the impact of some of the agricultural policies proposed by the European Union based on the bioeconomy and the circular economy, as well as the possible benefits that producers could obtain from their application. [11].

3.1. Crop Production

Commercial production varied significantly according to the treatments applied at the end of each year of study, as shown in Figure 1. The experimental plots that were not fertilized showed lower production than the rest of the treatments (IF, IFB1, IFB2, PD, PDB1, PDB2, IFPD, IFPD1, PD1, and PD2) during the three years of the trial. In turn, an expected behavior was observed—a progressive reduction in their final commercial production throughout the three years of research. The productive trend was different from that obtained by Ruiz-Olmos et al. [51] in a bell pepper crop between its treatment without fertilizer and mixed organic fertilization with papaya plant debris and coconut fiber incorporated through the biosolarization technique; however, it was analogous to that reported by Bilalis et al. [52] in a tomato crop intended for industry between the fertilized treatments (with organic or inorganic fertilizer) and that with only water added. In addition, the authors observed a decrease in the final yield of the treatment without fertilization during their experiment.



(**a**) (**b**) (**c**)

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. Values (mean ± standard deviation). Different letters indicate significant differences ($p \leq 0.05$, Tukey's HDS test). No fertilization (test); inorganic fertilization (IF); inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets (IFB1); inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets (IFB2); 3.5 kg·m^{-2} of tomato plant debris (PD); 3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets (PDB1); 3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets (PDB2); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2). * Source: own elaboration based on Castillo-Díaz et al. [23].

In general, treatments that received inorganic fertilization throughout the growing season (with or without *Brassica carinata* pellets or tomato plant debris) achieved similar final yields to treatments that were fertilized only with organic amendments (i.e., tomato plant debris with or without *Brassica carinata* pellets). However, when a dose of 1.0 kg·m^{-2} of *Brassica carinata* pellets was added to the inorganic mulch fertigation (IFB2), the final yield increased during the first two crop cycles compared to PD (Figure 1). It is worth mentioning the occurrence of an epidemic of *Botrytis cinerea*, which was impossible to control during the second growing cycle given the environmental conditions conducive to its appearance. The distribution of the disease was similar among all treatments (Kruskal–Wallis p-value: 0.1970) and caused an average mortality of 39.1 ± 18.7 %. The epidemic could have influenced the comparison of the final yield of the IF, IFB1, and PD treatments. Different authors have reported a similar result when comparing the final production of a tomato crop fertilized with inorganic fertilization versus exclusive nutrition with different organic amendments (compost, bone meal, blood or hoofs, chicken, sheep or turkey manure, and plant debris) [52–55]. In addition, in greenhouse agriculture in Almeria, nutrition with fresh sheep manure incorporated by the biosolarization technique has been proposed as a viable alternative to the reduction in organic fertilizers authorized by the organic production regulation of the European Union in winter tomato crop cycles. However, some research conducted in the same region has reported a significant decrease in the total yield of three cycles of long-term bell pepper crops fertilized with bell pepper plant debris, vegetable compost, and a small amount of inorganic fertilizer compared to conventional cultivation. The authors did not use the biosolarization technique [25]. In soils free of telluric diseases, the biosolarization technique has been described as a methodology capable of improving the chemical quality of soil, and with it, the productivity of the crop despite the application of inorganic cover crop fertilizers [36–38]. Therefore, the application of the biodisinfection protocol could have influenced the expression of our results. In addition, fresh plant debris can be associated with various pests and diseases, a common situation in a commercial production cycle. The biosolarization technique can help to reduce the inoculum present in the plant material [24,29].

Therefore, the results suggest that the use of plant by-products (fresh tomato plant debris) with biosolarization can be a viable alternative to the fertilizer reduction proposed by the European Union from a production point of view. The application of circular economy principles in terms of agricultural biomass management is an interesting opportunity for producers to increase the sustainability of their farms [11]. In addition to offering alternatives for the production of fruit and vegetables under European organic certification, which prohibits the use of inorganic fertilizers [56]. The European Union wants to increase its organic area to 25% of agricultural land by 2030 [18]. Therefore, the identification of circular production methods that can be used in organic production, such as the one presented here, is of great importance. However, the theoretical nutrient imbalance caused by the non-incorporation of the harvested fruits into the soil could lead to a loss of productivity in the long term [57], although this was not observed in our trial after repeating the production technique for three consecutive years and after being carried out in the same greenhouse for two years before the start of our trial [24]. This could be solved by adding manure to the plant debris. Specifically, the producers of the Almeria model carry out an application of animal by-products (fresh manure) every three or four years during the summer prior to transplanting crops, a process known as "broadcasting the manure" [8]. The work could be used to even out the nutrient balance if there is a long-term loss of yield. On the other hand, it would also be possible to add some type of organic or mineral fertilizer through the irrigation system at times when crops may suffer from biotic or abiotic stress. The measures proposed by the European Union intend to give priority to production methods that are harvested under organic certification. It is, therefore, more tempting to use organic or mineral fertilizers or other by-products that can be applied with plant debris, such as manure, than it is to add inorganic fertilizers while trying to comply with this certification to meet the sustainability goals set by the European Union [18,56]. However, a reduced input of inorganic fertilizers could also be made in crop production models where their use is allowed. In our trial, no inorganic, organic, or mineral fertilizers were applied to the Test, PD, PDB1, PDB2, PD1, or PD2 treatments by the irrigation system at any time during the experiment.

The results suggest that the combined addition of *Brassica carinata* pellets to the inorganic mulch fertilizer or the fresh tomato plant debris did not have a significant effect on the final commercial production of the IF and PD blocks (Table 4). However, due to the experimental design used in this research, it is not possible to provide a complete answer to the nutritive effect of the pelleted organic amendment by itself since there were not two treatments with 0.5 y 1.0 kg·m^{-2} of *Brassica carinata* pellets that were not fertilized with any other fertilizer. Thus, several authors have analyzed the effect of doses starting from 0.2 a 1.5 kg·m^{-2} of *Brassica carinata* pellets (with biosolarization) on the productive yield of different crops grown and have obtained a slight or significant increase in production compared to untreated or methyl bromide disinfected plots. However, some studies report the existence of soil-borne diseases caused by various pathogenic organisms where the material seems to partially limit the expression of the theoretical potential inoculum present in the soil [30,31,33,58] or the picture of the disease produced by the pathogenic organisms [30,31,33,40]. Therefore, the resulting increase in crop yields could be due to the reduction in production losses caused by telluric diseases. On the other hand, the material has been tested in combination with or in comparison to other organic amendments. Some of the organic materials have achieved a similar or superior effect to the single *Brassica carinata* pellet supply (e.g., fresh chicken manure, sugar beet vinasse, dried olive pomace, or fresh sheep manure) [30,31,33] (Table 5). Moreover, when the material was tested in pathogen-free soil with biosolarization, it also failed to achieve a significant increase in yield compared to treatment with inorganic mulch fertilization [24,36] or other organic amendments of plant origin [24]. In the third year of the trial, the various doses of plant debris applied to the IF and PD blocks also failed to achieve a significant increase in the final commercial production (Table 4). The trend obtained during the three years of testing is contrary to that reported by Mauromicale et al. [37,38]. The authors achieved a significant increase in the production of various tomato crops managed under commercial greenhouse practices by applying biosolarization in soils free of pathogenic organisms.

Table 4. Influence of *Brassica carinata* pellets (Crops 1 and 2) and tomato plant debris (Crop 3) on final commercial production in the IF and PD blocks.

	Crop 1	Crop 2	Crop 3
Block IF (p-value)	0.4992	0.7588	0.4999
Block PD (p-value)	0.6240	0.4160	0.2639

Block IF: analysis of variance (one-way ANOVA) performed between treatments IF, IFB1, and IFB2 in Cycles 1 and 2 and IF, IFPD, and IFPD1 in Cycle 3; block PD: analysis of variance (one-way ANOVA) performed between treatments PD, PDB1, and PDB2 in Cycles 1 and 2 and PD, PD1, and PD2 in Cycle 3.

Table 5. Effect of *Brassica carinata* pellets with biosolarization on the yield of several crops affected by soil pathologies.

Brassica carinata Pellet Doses	Crops	Soil Pathogen	Conduct	Source
0.2 to 1.5 kg·m^{-2}	Crops of strawberry, bell pepper, tomato, or asparagus grown under commercial farming practices.	*Fusarium* spp., *Meloidogyne* spp., *Pratylenchus penetrans*, *Phytophthora capsici* y *Macrophomina phaseolina*	Increased production compared to untreated plots.	[30,31,58]
			Increased yields compared to methyl bromide disinfected plots.	[33,40]

Source: own elaboration based on reports from other authors.

3.2. Crop Quality

The mass and equatorial diameter of tomato fruits did not show significant differences starting in the second year of the study between the treatments that were fertilized with or without the addition of inorganic cover crop fertilization (IF, IFB1, IFB2, PD, PDB1, PDB2, IFPD, IFPD1, PD1, and PD2), but did with respect to non-fertilization (Test). The Test treatment showed a trend similar to that observed in the final commercial production, that is, a progressive decrease in fruit mass and equatorial diameter during the experiment (Table 6). Thus, the addition of organic amendments to the IF block or their increased dosage in the PD block did not have a significant influence on fruit mass or equatorial diameter (Table 7). Bialis et al. [52] showed a partially similar trend in their tomato production cycles, finding differences in fruit mass between plots fertilized with inorganic fertilizer and unfertilized plots, but no differences in equatorial diameter. Mauromicale et al. [37,38] reported an increase in fruit mass in plots where solarization was combined with organic amendments versus those only solarized, although these authors incorporated inorganic fertilization into all their treatments.

The firmness, soluble solids, and fruit pulp pH showed variable trends during the trial. Although significant differences were observed during the first year of the trial for soluble solids and the fruit pulp pH, they were minimal (Table 6). A similar situation occurred in the independent comparison between blocks (Table 7). The results obtained are comparable to those reported by different studies that have analyzed the organoleptic quality of tomato fruits through exclusive fertilization with organic fertilizers versus conventional cultivation [53,55]. On the other hand, some studies have also reported an increase in the quality of the tomato crop harvest as a consequence of applying organic amendments [52], even when applied with biosolarization [38], a tendency that was not observed in our research.

Table 6. Tomato fruit yield and quality parameters in the three years of study (September–April cycles) as a function of crop nutrition. Values (mean ± standard deviation).

		Fruit Weight (g)	Size (mm)	Firmness (kg·m^{-2})	Soluble Solids (○Brix)	Fruit Acidity (pH)
Crop 1	Test *	108.20 ± 4.17 c	58.36 ± 0.40 c	5.15 ± 0.28 a	5.46 ± 0.14 a	3.91 ± 0.04 b
	IF *	125.18 ± 11.05 ab	63.53 ± 0.79 a	4.50 ± 0.19 b	5.01 ± 0.08 b	4.03 ± 0.03 a
	IFB1	131.26 ± 5.86 a	63.84 ± 0.39 a	4.64 ± 0.15 ab	4.93 ± 0.03 b	4.00 ± 0.03 a
	IFB2	131.63 ± 2.36 a	63.78 ± 0.65 a	4.39 ± 0.43 b	5.01 ± 0.04 b	3.98 ± 0.02 a
	PD	115.83 ± 4.34 bc	60.84 ± 1.00 b	4.56 ± 0.18 ab	5.47 ± 0.11 a	4.01 ± 0.03 a
	PDB1	117.69 ± 4.13 bc	61.61 ± 1.04 b	4.41 ± 0.11 b	5.30 ± 0.22 a	4.01 ± 0.03 a
	PDB2	122.77 ± 6.09 ab	62.27 ± 1.06 ab	4.65 ± 0.58 ab	5.29 ± 0.03 a	4.01 ± 0.06 a
	p-value	0.0000	0.0000	0.0469	0.0000	0.0031
Crop 2	Test *	99.06 ± 4.87 b	56.59 ± 1.67 b	5.08 ± 0.20 bc	5.50 ± 0.21	4.2 ± 0.02
	IF *	126.59 ± 3.87 a	62.66 ± 0.56 a	4.84 ± 0.16 c	5.28 ± 0.19	4.23 ± 0.05
	IFB1	121.80 ± 4.72 a	62.18 ± 0.99 a	5.27 ± 0.39 ab	5.38 ± 0.14	4.21 ± 0.03
	IFB2	119.74 ± 5.61 a	60.96 ± 1.24 a	5.57 ± 0.14 ab	5.69 ± 0.03	4.2 ± 0.02
	PD *	114.70 ± 11.05 a	60.29 ± 2.52 a	5.38 ± 0.20 ab	5.53 ± 0.36	4.17 ± 0.06
	PDB1	117.26 ± 7.58 a	61.36 ± 1.89 a	5.39 ± 0.24 ab	5.38 ± 0.16	4.17 ± 0.02
	PDB2	120.45 ± 8.52 a	60.94 ± 1.32 a	5.35 ± 0.32 a	5.44 ± 0.29	4.16 ± 0.01
	p-value	0.0007	0.0006	0.0119	0.2599	0.0930
Crop 3	Test *	72.08 ± 4.06 b	50.18 ± 1.13 b	5.33 ± 0.21 a	5.64 ± 0.11	3.85 ± 0.03 ab
	IF *	104.69 ± 4.79 a	59.18 ± 1.04 a	4.78 ± 0.88 ab	5.54 ± 0.15	3.85 ± 0.02 ab
	IFPD	97.65 ± 10.57 a	57.92 ± 2.17 a	4.57 ± 0.39 ab	5.66 ± 0.29	3.82 ± 0.02 b
	IFPD1	99.46 ± 3.34 a	57.77 ± 0.77 a	4.03 ± 0.24 b	5.70 ± 0.15	3.84 ± 0.02 ab
	PD *	95.64 ± 10.76 a	56.71 ± 2.43 a	4.00 ± 0.41 b	5.58 ± 0.25	3.89 ± 0.03 a
	PD1	101.79 ± 3.55 a	57.96 ± 0.23 a	4.27 ± 0.14 b	5.43 ± 0.17	3.85 ± 0.04 ab
	PD2	103.46 ± 4.76 a	58.63 ± 0.87 a	4.41 ± 0.15 ab	5.37 ± 0.16	3.88 ± 0.00 a
	p-value	0.0000	0.0000	0.0028	0.1796	0.0215

Different letters indicate significant differences ($p \leq 0.05$, Tukey's HDS test). No fertilization (test); inorganic fertilization (IF); inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets (IFB1); inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets (IFB2); 3.5 kg·m^{-2} of tomato plant debris (PD); 3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets (PDB1); 3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets (PDB2); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2). * Source: own elaboration based on Castillo-Díaz et al. [23].

Table 7. Influence of *Brassica carinata* pellets (Crops 1 and 2) and tomato plant debris (Crop 3) on tomato fruit quality parameters in the IF and PD blocks.

Crop	Parameter	Block IF (*p*-Value)	Block PD (*p*-Value)
1	Fruit Weight	0.1646	0.1755
	Size	0.7658	0.2026
	Firmness	0.4964	0.6403
	Soluble Solids	0.0873	0.1824
	Fruit Acidity	0.0836	0.9688
2	Fruit Weight	0.1720	0.6845
	Size	0.0849	0.7500
	Firmness	0.0096	0.9691
	Soluble Solids	0.0068	0.7703
	Fruit Acidity	0.6147	0.8709
3	Fruit Weight	0.3739	0.3074
	Size	0.3645	0.2377
	Firmness	0.2105	0.1457
	Soluble Solids	0.5374	0.3325
	Fruit Acidity	0.1242	0.1657

Block IF: analysis of variance (one-way ANOVA) performed between treatments IF, IFB1, and IFB2 in Cycles 1 and 2 and IF, IFPD, and IFPD1 in Cycle 3; block PD: analysis of variance (one-way ANOVA) performed between treatments PD, PDB1, and PDB2 in Cycles 1 and 2 and PD, PD1, and PD2 in Cycle 3.

3.3. Evaluation of Seedling Growth in a Controlled Environment Chamber

The vigor tests carried out in the controlled environment chamber allowed for the observance of a possible improvement in soil quality in the experimental plots where organic amendments were added, which was observed with more clarity in the leaf area of the vegetable seedlings (Figures 2 and 3). The results suggest that the addition of the highest dose of organic amendments during each year of the trial (PDB2 and PD2) caused a superior enhancement of vigor parameters (i.e., number of leaves, height, aerial dry mass, root dry mass, and leaf area) of both plant species (i.e., cucumber and tomato seedlings). At the end of the trial, the leaf area of the treatments where only fresh tomato plant debris was applied (PD, PD1, and PD2) was superior to all treatments that received inorganic mulch fertilization (IF, IFPD, and IFPD1) in both plant species. Only IFPD was able to match PD in the leaf area of tomato seedlings. The production of fruits and vegetables under the principles of the circular economy, through the reuse of agricultural biomass, seems to have benefits on soil fertility, offering a source of internal and low-cost organic amendment to apply in the soil of the agricultural plots of the producers.

The treatment without fertilization (Test) obtained a leaf area similar to the treatments with inorganic mulch fertilization (IF, IFPD, and IFPD1) at the end of the experiment in both plant species. The leaf areas of cucumber and tomato seedlings reflected a greater sensitivity to the effect of soil disinfection techniques. The parameter increased in the samples taken after the end of the solarization or biosolarization protocol, including the treatment without fertilization. After the end of cultivation, the variable decreased. This behavior could reflect a depletion of soil nutrients, mainly potassium available for the crop [23]. On the other hand, Marín-Guirao et al. [44] reported an increase in vigor parameters (No. of leaves, height, aerial dry mass, root dry mass, and leaf area) of cucumber and tomato seedlings after applying biosolarization in a greenhouse where a commercial cucumber crop was grown, a performance partially similar to that observed in our research. This increase in vigor has also been reported after the addition of organic amendments to almond crops versus conventional management in the provinces of Almeria and Granada [45,46].

The addition of various doses of organic amendments (i.e., fresh tomato plant debris with or without *Brassica carinata* pellets) had an influence on the aerial dry mass and the leaf area of cucumber and tomato seedlings in the PD block (Table 8). This behavior was not obtained in the IF block. However, in the last year of the trial, a treatment with 6.5 $kg \cdot m^{-2}$ of fresh tomato plant debris was not incorporated into the inorganic fertilization. This fact could have influenced the expression of the results. However, adding various doses of organic amendments had a greater effect on the soil quality of the experimental plots in the PD block than that obtained in the IF block (Figures 2 and 3 and Table 8). This difference could be due to the type and dose of the organic amendment mostly used in both blocks (Figures 2 and 3 and Table 8). In the IF block, *Brassica carinata* pellets were used repeatedly, while in the PD block, it was tomato plant debris. Núñez-Zofio et al. [34] and Serrano-Pérez et al. [59] reported that *Brassica carinata* pellets (with biosolarization) showed a limited capacity to improve the chemical quality of the soil. The organic amendment could not improve any of the chemical properties of the soil versus a treatment without the addition of any organic amendment and without applying solarization. On the other hand, Castillo-Díaz et al. [23] stated that tomato plant debris had the potential to improve some of the chemical properties of the soil, such as assimilable potassium or total nitrogen, compared to inorganic fertilization.

3.4. Irrigation Water

In the third tomato crop cycle, irrigation was reduced by 37.2% in the PD block compared to the IF block (Figure 4). The addition of organic amendments to the soil through the biosolarization technique has been described as a methodology capable of modifying the infiltration rate of a soil [23,35], which has implications on the frequency and water allocation applied to the crop. Specifically, the results suggest how the improvement in soil hydraulic conductivity (Kh) reported by Castillo-Díaz et al. [23] could be extended to all experimental plots that repeatedly received fresh tomato plant debris during the three years of investigation; this shows the advantages of using a production model based on the circular economy.

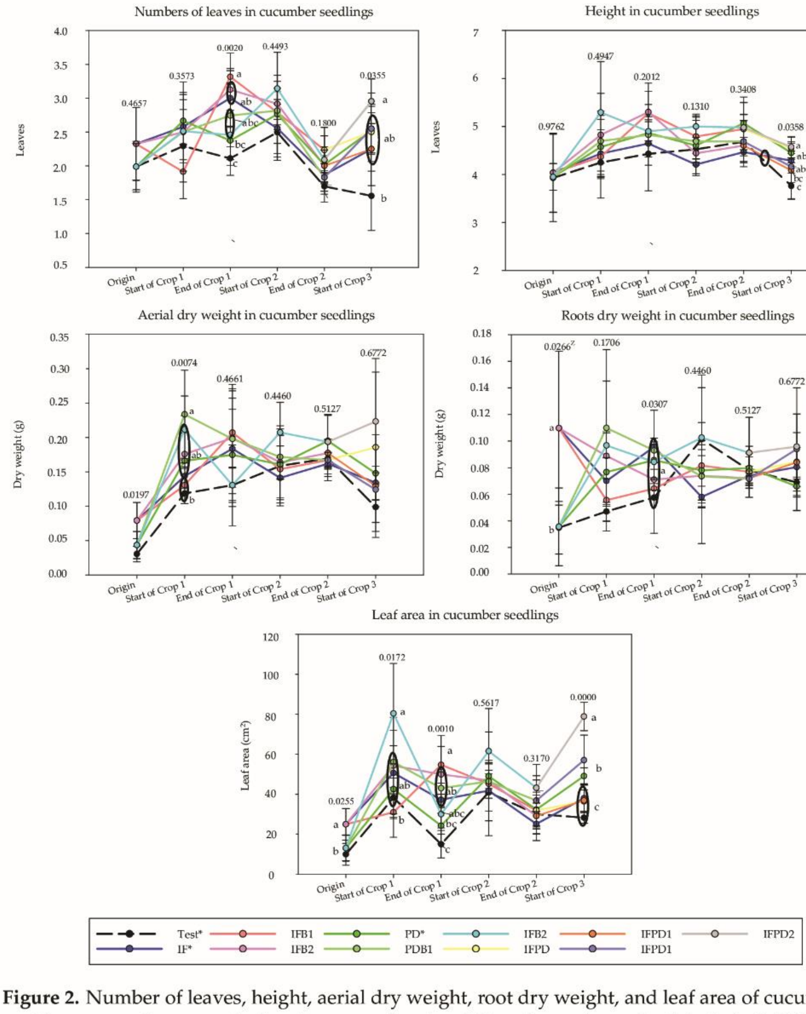


Figure 2. Number of leaves, height, aerial dry weight, root dry weight, and leaf area of cucumber seedlings grown in a controlled environment chamber. Values (mean ± standard deviation). Different letters indicate significant differences ($p \leq 0.05$, Tukey's HDS test; z: $\sqrt{x}$). No fertilization (test); inorganic fertilization (IF); inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets (IFB1); inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets (IFB2); 3.5 kg·m^{-2} of tomato plant debris (PD); 3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets (PDB1); 3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets (PDB2); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2). * Source: own elaboration based on Castillo-Díaz et al. [23].

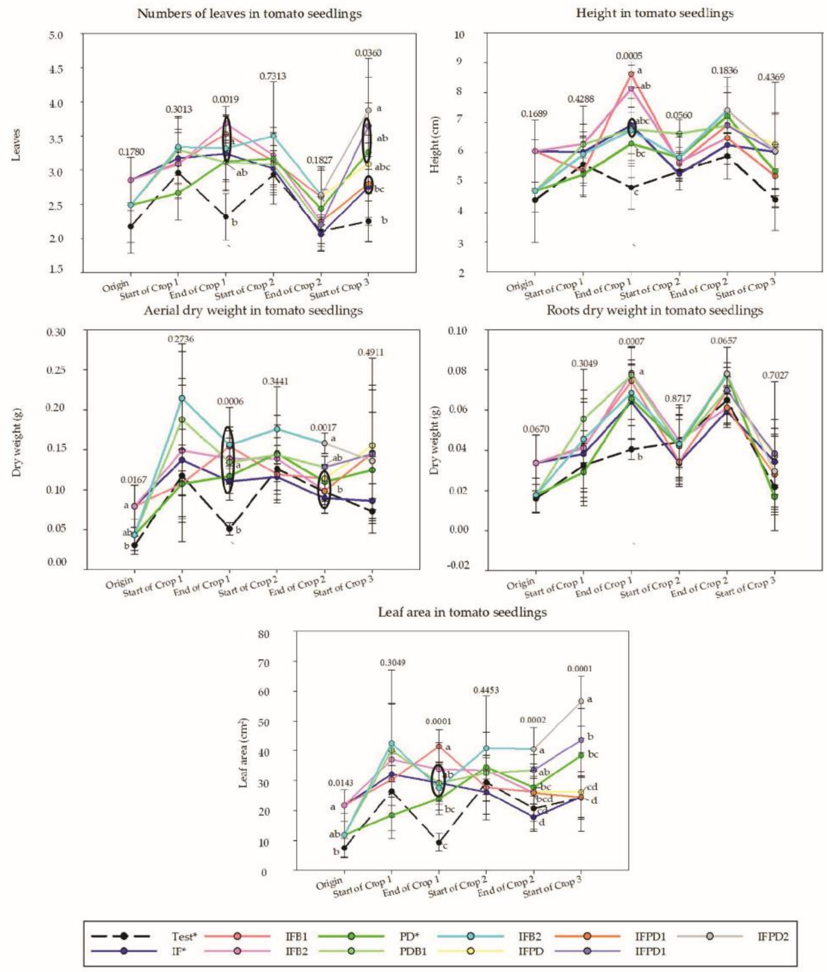


Figure 3. Number of leaves, height, aerial dry weight, root dry weight, and leaf area of tomato seedlings grown in a controlled environment chamber. Values (mean ± standard deviation). Different letters indicate significant differences ($p \leq 0.05$, Tukey's HDS test). No fertilization (test); inorganic fertilization (IF); inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets (IFB1); inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets (IFB2); 3.5 kg·m^{-2} of tomato plant debris (PD); 3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets (PDB1); 3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets (PDB2); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2). *Source: own elaboration based on Castillo-Díaz et al. [23].

Table 8. Influence of Brassica carinata pellets (Crops 1 and 2) and tomato plant debris (Crop 3) on leaf number, height, aerial dry weight, root dry weight, and leaf area in cucumber and tomato seedlings grown in a controlled environment chamber in IF and PD blocks.

Crop	Sampling	N° of Leaves		Height		Aerial Dry Weight		Roots Dry Weight		Leaf Area	
		IF Block	PD Block	IF Block	PD Block	IF Block	PD Block	IF Block	PD Block	IF Block	PD Block
Cucumber											
1	Start	0.1824	0.8695	0.6689	0.4182	0.2479	0.2286	0.4426	0.5006	0.1872	0.0560
	End	0.5620	0.4292	0.1298	0.9683	0.8922	0.3354	0.0664	0.5854	0.2770	0.0436
2	Start	0.4380	0.5082	0.0951	0.4470	0.6843	0.3302	0.6633	0.4228	0.9218	0.2737
	End	0.2383	0.4350	0.1376	0.5572	0.6294	0.4165	0.8572	0.3019	0.6381	0.4175
3	Start	0.7674	0.2034	0.2839	0.1206	0.5469	0.0972	0.9724	0.3410	0.9322	0.0023
	End	-	-	-	-	-	-	-	-	-	-
Tomato											
1	Start	0.9404	0.0990	0.1131	0.3292	0.7420	0.1277	0.9683	0.2698	0.7474	0.1650
	End	0.2938	0.7314	0.1492	0.6741	0.0836	0.3375	0.3740	0.4806	0.0971	0.5740
2	Start	0.7588	0.5606	0.3270	0.2061	0.3539	0.5716	0.3580	0.9952	0.3453	0.6542
	End	0.1322	0.3839	0.5424	0.7143	0.4249	0.0042	0.3339	0.3661	0.1400	0.0247
3	Start	0.7973	0.4408	0.6075	0.6317	0.4537	0.8901	0.8809	0.1636	0.9564	0.0366
	End	-	-	-	-	-	-	-	-	-	-

Block IF: analysis of variance (one-way ANOVA) performed among treatments IF, IFB1, and IFB2 in Cycles 1 and 2 and IF, IFPD, and IFPD1 in Cycle 3; block PD: analysis of variance (one-way ANOVA) performed among treatments PD, PDB1, and PDB2 in Cycles 1 and 2, and PD, PD1, and PD2 in Cycle 3.

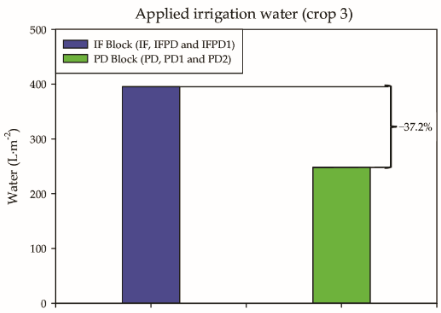


Figure 4. Irrigation water applied in the IF and PD blocks during the third cycle of tomato cultivation. Inorganic fertilization (IF); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 3.5 kg·m^{-2} of tomato plant debris (PD); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2).

3.5. Economic Analysis

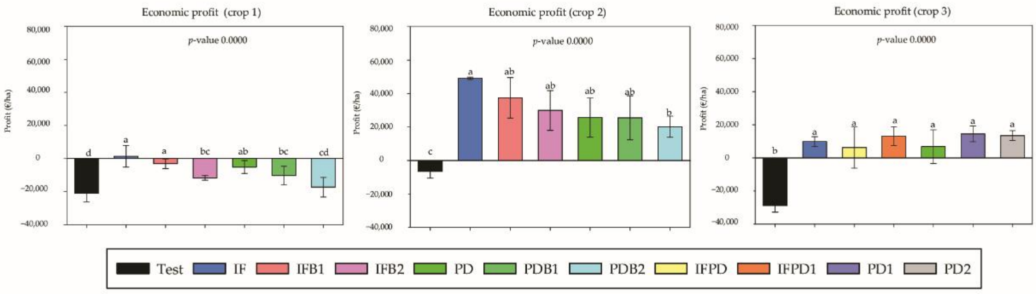
3.5.1. Analysis 1

Table A1 (see Appendix A) shows the cost structure of the treatments used during the research (Test, IF, IFB1, IFB2, PD, PDB1, PDB2, IFPD, IFPD1, PD1, and PD2). It can be observed that non-fertilization (Test) and exclusive fertilization based on the reuse of fresh tomato plant debris produced in the greenhouse (PD, PD1, and PD2) resulted in a decrease in production costs of up to 4.8% compared to conventional inorganic fertilization (IF). Precisely, this benefit was achieved by the reduced need for agricultural inputs and services. In some cases, the reduction involved inputs such as inorganic fertilizers or irrigation water, whose excessive consumption can deteriorate the sustainability of ecosystems [9,18,60]. Duque-Acevedo et al. [11] reported that the utilization of plant biomass in tomato cycles of eleven months could cause a decrease in the cost account of approximately 0.5 %. The authors contemplated a lower reduction in inorganic fertilizers and irrigation water than the one obtained in our work. Mixed fertilization based on fresh tomato plant debris and inorganic fertilizer increased production costs by 0.2% while adding *Brassica carinata* pellets showed an increase of up to 22% due to the price of the organic amendment and the dose added into the soil.

On the other hand, the cost of incorporating plant debris into the soil for reuse was lower than reported by Torres-Nieto et al. [49] due to the decreased labor required to separate the trellising raffia from the tomato plants. That was due to not using trellising clips, and also because the greenhouse soil was not the typical one of the Almeria model, so the tomato plant debris could be incorporated on the surface. In this sense, the use of sandblasted soil to produce fruit and vegetables in greenhouse agriculture in Almeria is habitual, mainly because it prevents salts from rising from the deep soil profiles [8]. Therefore, the cost of incorporating plant debris into the soil could increase from that reported in this trial since the expense of other tasks related to the opening of the sand and its leveling would have to be charged. However, other alternatives can reduce this expense, such as introducing the plant material through layers placed on the crop line (triangular trenches of approximately 0.3 m in height and 0.4 m in base) [8,49]. Moreover, the use of this methodology could have other benefits. Plant debris is produced to a limited extent on the culture surface [12]. Therefore, using banding would increase the doses of plant debris incorporated into the soil due to a concentration of the plant by-product in space, which would also coincide with the soil profile explorable by plant roots.

Figure 5 shows the annual pre-tax profit of the treatments applied during the research (Test, IF, IFB1, IFB2, PD, PDB1, PDB2, IFPD, IFPD1, PD1, and PD2). The losses in some of the treatments because of the low price received by the producers at origin (crop 1) and the low productivity of some of the treatments (Test) can be noticed. Thus, the addition of *Brassica carinata* pellets significantly reduced the profit of the experimental plots that received the material. Exclusive fertilization through the reuse of 3.5 $kg \cdot m^{-2}$ of fresh tomato plant debris obtained a similar annual benefit to inorganic cover crop fertilization (IF). However, the PD treatment achieved a lower average annual value than IF. This could negatively influence the cumulative benefit of the alternative production system. In the third year of the trial, despite no significant differences between treatments being observed, the exclusive fertilization based on reusing 5.0 $kg \cdot m^{-2}$ f fresh tomato plant debris achieved the highest annual benefit. Therefore, the results illustrate how the self-management of plant debris incorporated through the biosolarization technique can be postulated as a profitable and sustainable alternative to the reduction in fertilizers proposed by the European Union [18], and the framework of the bioeconomy and the circular economy. However, the use of external high-value organic amendments can cause a disturbance in the profitability of the agricultural model as a result of the reduction in the profit margin experienced by farmers and the stability of prices at the source in recent years [2].

Therefore, the use of plant by-products (i.e., tomato plant debris) through the biosolarization technique seemed to achieve different benefits over the different means of production used to obtain the product in industrial agriculture, such as the one carried out in the greenhouses in the province of Almeria. In our case, the results suggest not only similar productivity after the fertilization of a commercial tomato crop from a green manure to the agricultural biomass generated by the previous crop, but also higher soil fertility, a further reduction in crop water consumption and similar economic performance to the conventional crop, while plant biomass management seemed to be improved in the production model. In this way, production under the principles of the circular economy (i.e., reduce, reuse, and recycle) shows different benefits for agricultural production systems. These align with the objectives set by the European Union in terms of agriculture and also offer alternatives so that producers under European organic certification can have a battery of farming techniques with which to meet the challenges of sustainability without lowering their economic profit, even though the prices at the source that farmers receive have remained stable over the last decade.



(**a**) (**b**) (**c**)

Figure 5. Pre-tax economic benefit in the three years of study in September–April tomato cycles as a function of crop nutrition: (**a**) Crop 1; (**b**): Crop 2; (**c**): Crop 3. Values (mean ± standard deviation). Different letters indicate significant differences ($p \leq 0.05$, Tukey's HDS test). No fertilization (test); inorganic fertilization (IF); inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets (IFB1); inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets (IFB2); 3.5 kg·m^{-2} of tomato plant debris (PD); 3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets (PDB1); 3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets (PDB2); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2). Source: own elaboration based on Torresano and Camacho-Ferre [47], Honore et al. [2], Junta de Andalucia [48], Torres-Nieto [49], and specialized agricultural supply centers.

3.5.2. Analysis 2

The cost structure of the five horticultural alternatives evaluated according to the experimental results obtained in this work is shown in Table 9. The application of a circular production model, through the reuse of fresh plant debris using the biosolarization technique, would reduce production costs by 3.3% regardless of whether or not the inorganic fertilization of the mulch is reduced. The reduction results from the "variable costs" due to the substitution of some traditional inputs via by-products and agroecological techniques. Production Methodology 2 experiences decreases of 100% in the cost of external management of crop residues, 100% in the cost of chemical soil disinfectants, and 37.2% in water. Methodology 3 also offers a 100% reduction in inorganic fertilization in the autumn–winter crop and a 38.7% reduction in the spring–summer crop (see Appendix A, Table A2).

Table 9. Reduction in production costs compared to the conventional production method in the Almeria model.

	Alternative 1 (%)	Alternative 2 (%)	Alternative 3 (%)	Alternative 4 (%)	Alternative 5 (%)	Mean (%)
Methodology 1	-	-	-	-	-	-
Methodology 2	2.2	2.0	2.0	2.1	1.3	1.9 ± 0.3
Methodology 3	5.6	4.6	4.5	4.3	4.1	4.6 ± 0.6

Methodology 1: conventional; **Methodology 2**: self-management of plant debris and reduction in water, soil management, and chemical soil disinfectants; **Methodology 3:** Methodology 2 + reduction of inorganic fertilization. Source: own elaboration based on Torresano and Camacho-Ferre [47], Honore et al. [2], Junta de Andalucia [48], Torres-Nieto [49], and specialized agricultural supply centers.

However, despite the reduction in production costs experienced through Methodologies 1 and 2, four of the five horticultural alternatives presented economic losses in the 2016–2021 interval. Only the fifth crop alternative, which mainly used tomato monoculture, obtained benefits (Figure 6). The reuse of vegetable waste can slightly increase profitability, but it cannot fully correct the losses suffered in the first four alternatives due to the stability of prices at origin and the increase in production costs [2].

The situation described prompted us to reflect on the continuity of the Almeria model in terms of economic profitability. Two elements have a significant influence on this situation. One of them is the disbursement of labor, which may represent from 21.19% to 86.44% of the annual campaign expenses depending on the type of crop used [2,47]. Valera et al. [8] reported that the owner of the farm is part of the labor force. For this reason, in periods of low profitability or economic losses, he/she refuses all or part of the remuneration that corresponds to him/her as the owner and resorts, if necessary, to reducing the number of employees or substituting them with family labor that receives lower economic remuneration.

On the other hand, the various depreciation costs of the different production structures (greenhouse and auxiliary structures), which account for most of the fixed costs of the farm, also play a role. Thus, on farms with a low debt ratio, the outlay on this item, and thus, the economic losses, could be reduced [2]. Therefore, the utilization of agricultural by-products, such as the reuse of plant debris from the previous crop, can contribute to reducing crop losses [11] in synergy with these items (amortization of production structures and labor) [2].

The introduction of new crops has been recommended to diversify and increase the range of products offered in the Almeria model. The current range is composed of eight horticultural products classified as commodities. Honore et al. [2] proposed the cultivation of papaya as a viable alternative to the traditional fruit and vegetable crops used in greenhouse agriculture in Almeria, obtaining a high economic benefit.

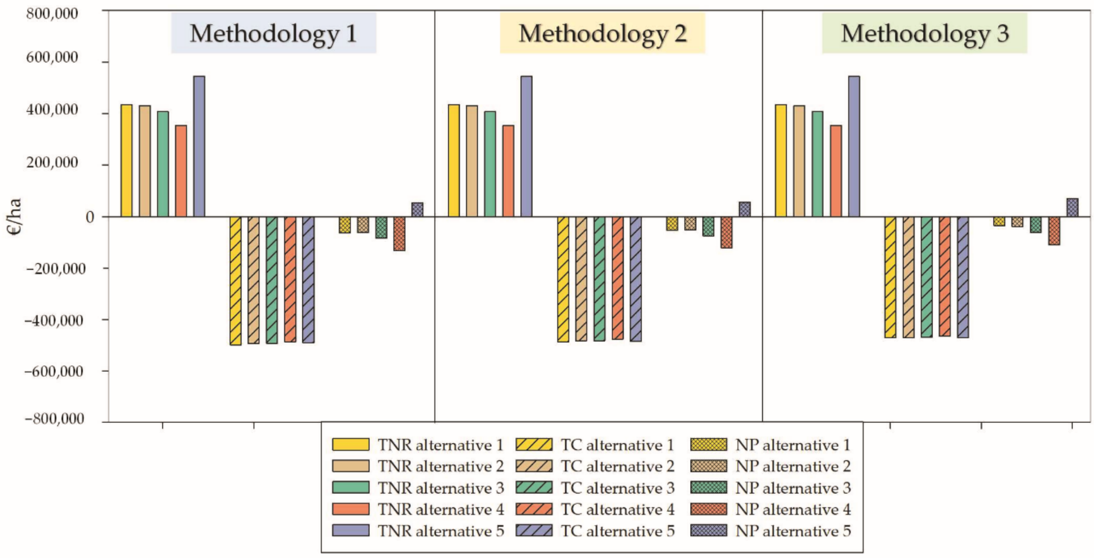


Figure 6. Comparison of the economic performance of the five horticultural alternatives evaluated from February 2016 to January 2021. **Methodology 1:** conventional; **Methodology 2**: self-management of plant debris and reduction in water, soil management, and chemical soil disinfectants; **Methodology 3:** Methodology 2 + reduction of inorganic fertilization; TNR: total income; TC: total costs; NP: economic benefit. Source: own elaboration based on Torresano and Camacho-Ferre [47], Honore et al. [2], Junta de Andalucia [48], Torres-Nieto [49], and specialized agricultural supply centers.

4. Conclusions

The results of this research suggest that exclusive fertilization based on organic amendments with biosolarization can be postulated as an alternative to reducing fertilizers as proposed by the European Union, maintaining similar productivity and economic crop yields versus conventional crops fertilized with inorganic fertilizers in production cycles up to 217 DAT. However, the use of a circular production model, through the reuse of plant debris, shows a greater advantage. Reusing vegetal by-products can help producers to solve the problems linked to the external management of the material, as well as reduce production costs for Almeria farmers by up to 4.8%. This, in turn, can help to mitigate the low economic return that producers register given the stability of the prices at origin of fruits and vegetables. The addition of organic amendments of high economic value can alter the profitability of the agricultural system by increasing production costs by up to 22% and having a similar effect on tomato crop production as agricultural biomass when combined with agricultural biomass or inorganic fertilization. Therefore, the practice of reusing plant debris should be more widely implemented in agricultural systems to increase the sustainability of agricultural models with a method that falls under the principles of the circular economy. This can lead to benefits, such as improved soil fertility, that can translate into reductions in water consumption, which, in our trial, was 37.2%. Future research should analyze the effect of other types of plant biomass (i.e., other horticultural species, plant waste from parks or gardens, or pruning waste from fruit species) as a sole source of fertilizer for commercial crops with longer crop production cycles to increase the knowledge of this method of production and provide producers with a range of techniques with which they can increase the sustainability of their farms.

Author Contributions: Conceptualization, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; data curation, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; formal analysis, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; investigation, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; methodology, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; project administration, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; Resources, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; software, F.J.C.-D. and L.J.B.-U.; supervision, L.J.B.-U., F.C.-F. and J.C.T.M.; validation, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; visualization, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; writing—original draft, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M.; writing—review and editing, F.J.C.-D., L.J.B.-U., F.C.-F. and J.C.T.M. All authors have read and agreed to the published version of the manuscript.

Funding: The present research has not received any funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors wish to thank the dedication of the members of the AGR-200 Research Group of the University of Almeria, especially César Antonio Ruiz Olmos, and the UAL-ANECOOP Experimental Farm.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Cost structure per hectare of the treatments used during the research in the three tomato crop cycles.

		Crop 1							Crop 2							Crop 3						
		Test	IF	IFB1	IFB2	PD	PDB1	PDB2	Test	IF	IFB1	IFB2	PD	PDB1	PDB2	Test	IF	IFPD	IFPD2	PD	PD1	PD2
Variable Cost (€/ha)	Technical assessment				153 [1]							152 [1]							155 [1]			
	Soil preparation				0 [1]							0 [1]							0 [1]			
	Removal of plant debris	998	998	998	998	0	0	0	990	990	990	990	0	0	0	1005	1005	0	0	0	0	0
	PD incorporation	0	0	0	0	1171	1171	1171	0	0	0	0	1161	1161	1161	0	0	1179	1179	1179	1179	1179
	Solarization				1714 [1]							1700 [1]							1725 [1]			
	Water for solarization	225	225	225	225	141	141	141	223	223	223	223	140	140	140	226	226	226	226	142	142	142
	Chemical disinfectant				0 [1]							0 [1]							0 [1]			
	Brassica carinata pellets	0	0	7569	15,139	0	7569	15,139	0	0	7509	15,018	0	7509	15,018				0 [1]			
	Banding	0	0	525	525	0	525	525	0	0	521	521	0	521	521				0 [1]			
	Covering and structure				2356 [1]							2337 [1]							2372 [1]			
	Seeds and seedling production				5683 [1]							5638 [1]							5722 [1]			
	Labor, inputs, etc.				34,390 [1]							34,115 [1]							34,627			
	Water	2957	2957	2957	2957	1857	1857	1857	2933	2933	2933	2933	1842	1842	1842	2977	2977	2977	2977	1870	1870	1870
	Fertilizers	0	2480	2480	2480	0	0	0	0	2460	2460	2460	0	0	0	0	2497	2497	2497	0	0	0
Fixed Costs (€/ha)	Soil maintenance				2044 [1]							2028 [1]							2075 [1]			
	Covering and structure				4092 [1]							4060 [1]							4153 [1]			
	Energy and fixed supplies				1617 [1]							1604 [1]							1641 [1]			
	IMF				3558 [1]							3530 [1]							3611 [1]			
	Equipment and irrigation system				10,183 [1]							10,101 [1]							10,334 [1]			
	Total cost	69,970	72,451	80,545	88,114	68,960	77,054	84,624	69,411	71,871	79,901	87,409	68,408	76,438	83,947	70,622	73,120	73,294	73,294	69,605	69,605	69,605
	Variation with IF (%)	−3.4	0.0	11.2	21.6	−4.8	6.4	16.8	−3.4	0.0	11.2	21.6	−4.8	6.4	16.8	−3.4	0.0	0.2	0.2	−4.8	−4.8	−4.8

[1] Common cost for all treatments and cultivation. IMF: insurance, management, and financial services. No fertilization (test); inorganic fertilization (IF); inorganic fertilization + 0.5 kg·m^{-2} of *Brassica carinata* pellets (IFB1); inorganic fertilization + 1.0 kg·m^{-2} of *Brassica carinata* pellets (IFB2); 3.5 kg·m^{-2} of tomato plant debris (PD); 3.5 kg·m^{-2} of tomato plant debris + 0.5 kg·m^{-2} of *Brassica carinata* pellets (PDB1); 3.5 kg·m^{-2} of tomato plant debris + 1.0 kg·m^{-2} of *Brassica carinata* pellets (PDB2); inorganic fertilization + 3.5 kg·m^{-2} of tomato plant debris (IFPD); inorganic fertilization + 5 kg·m^{-2} of tomato plant debris (IFPD1); 5 kg·m^{-2} of tomato plant debris (PD1); 6.5 kg·m^{-2} of tomato plant debris (PD2). Source: own elaboration based on Torresano and Camacho-Ferre [47], Honore et al. [2], Junta de Andalucia [48], Torres-Nieto [49], and specialized agricultural supply centers.

Table A2. Comparison of the cost structure of five horticultural alternatives under three production methodologies from February 2016 to June 2021.

		Alternative 1			Alternative 2			Alternative 3			Alternative 4			Alternative 5		
		M1	**M2**	**M3**	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**
Variable Cost (€/ha)	Total variable cost	398,957	388,173	371,107	393,216	383,165	370,519	392,649	382,683	370,380	386,826	376,636	366,121	383,050	375,905	362,073
	Technical assessment	1563	1563	1563	1563	1563	1563	1563	1563	1563	1563	1563	1563	1563	1563	1563
	Soil preparation	39,429	28,830	28,830	39,429	28,830	28,830	39,429	28,830	28,830	39,429	28,830	28,830	27,556	20,149	20,149
	Removal of plant debris	10,167	0	0	10,167	0	0	10,167	0	0	10,167	0	0	7124	0	0
	PD incorporation	0	9446	9446	0	9446	9446	0	9446	9446	0	9446	9446	0	7058	7058
	Solarization	4365	8730	8730	4365	8730	8730	4365	8730	8730	4365	8730	8730	4372	8730	8730
	Water for solarization	582	719	719	582	719	719	582	719	719	582	719	719	582	719	719
	Chemical disinfectant	514	0	0	514	0	0	514	0	0	514	0	0	514	0	0
	Covering and structure	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004	24,004
	Seeds and seedling production	40,146	40,146	40,146	46,458	46,458	46,458	53,523	53,523	53,523	43,882	43,882	43,882	32,308	32,308	32,308
	Labor and inputs	246,736	246,736	246,736	240,963	240,963	240,963	234,534	234,534	234,534	236,291	236,291	238,967	255,389	255,389	255,389
	Water	9279	5827	5827	7309	4590	4590	7079	4446	4446	7684	4826	4826	9843	6182	6182
	Fertilizers	22,171	22,171	5105	17,861	17,861	5215	16,887	16,887	10,350	15,669	15,669	5154	19,744	19,804	5971
Fixed Costs (€/ha)	Total fixed costs	99,397	99,397	99,397	99,397	99,397	99,397	99,397	99,397	99,397	99,397	99,397	99,397	108,230	109,214	109,214
	Soil maintenance	10,415	10,415	10,415	10,415	10,415	10,415	10,415	10,415	10,415	10,415	10,415	10,415	10,514	10,514	10,514
	Covering and structure	20,847	20,847	20,847	20,847	20,847	20,847	20,847	20,847	20,847	20,847	20,847	20,847	21,048	21,048	21,048
	Energy and fixed supplies	8234	8234	8234	8234	8234	8234	8234	8234	8234	8234	8234	8234	8311	8311	8311
	IMF	18,130	18,130	18,130	18,130	18,130	18,130	18,130	18,130	18,130	18,130	18,130	18,130	18,303	18,303	18,303
	Equipment and irrigation system	41,772	41,772	41,772	41,772	41,772	41,772	41,772	41,772	41,772	41,772	41,772	41,772	50,053	51,037	51,037

IMF: insurance, management, and financial services. Methodology 1: conventional; Methodology 2: self-management of plant debris and reduction of water, soil management, and chemical soil disinfectants; Methodology 3: Methodology 2 + reduction of inorganic fertilization; TNR: total income; TC: total costs; NP: economic benefit. Source: own elaboration based on Torresano and Camacho-Ferre [47], Honore et al. [2], Junta de Andalucia [48], Torres-Nieto [49], and specialized agricultural supply centers.

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LIMITACIONES DE LOS TRABAJOS

1. Limitaciones

Con este trabajo se desea contribuir al conocimiento de la gestión de los residuos agrícolas bajo el marco de la economía circular en la agricultura bajo invernadero de la provincia de Almería. Para ello se han realizado diferentes trabajos, observándose en este documento de tesis dos tipologías de manuscritos claramente diferenciados entre sí: análisis de revisión e investigaciones de campo. Con ellos se ha permitido conocer el estado del tratamiento de los plásticos en Almería, una temática no muy analizada de manera íntegra por la literatura científica; y la viabilidad agronómica y económica de sustituir de manera íntegra los fertilizantes inorgánicos de síntesis por una fuente nutritiva compuesta por restos vegetales de la campaña anterior y solarización en ciclos largos de producción de tomate. Sin embargo, la investigación, al igual que todos los trabajos de carácter experimental, no está exenta de limitaciones, las cuales se obtienen de manera intrínseca de los métodos usados o los antecedentes a los ensayos que causan barreras de difícil o imposible enmienda, a pesar de aplicar la máxima rigurosidad en cada etapa experimental.

Análisis de revisión

En los análisis de revisión han podido influir la inexistencia de análisis previos similares al realizado en esta investigación acerca del estado actual de los plásticos agrícolas en la agricultura bajo invernadero de Almería. La información necesaria se encontraba dispersa en una amplia batería de publicaciones lo que ha dificultado su búsqueda para su posterior análisis.

Además, la revisión efectuada implicó consultar diferentes de bases de datos, tanto de carácter primario como secundario. Los parámetros de búsqueda establecidos han podido condicionar los resultados obtenidos, además, del sesgo personal del investigador [1].

Ensayos de campo

Las limitaciones de los ensayos de campo pueden englobarse en dos grupos.

El primero compete a los factores que influyen sobre la producción final comercial del cultivo. Aquí se puede resaltar a la incidencia de las plagas y enfermedades que se desarrollan de manera espontánea sobre el cultivo y la degradación edáfica que sufría el cuarto suroeste del invernadero a causa de verter 8,1 m^3 de lodos del corte del mármol con una concentración elevada en carbonato cálcico durante la campaña 2009/2010 en carillas alternas [2]. Esta degradación pudo verse agravada por la deshidratación previa que sufrió el material bajo las limitaciones de mano de obra que se originaron durante la aplicación del subproducto cálcico.

Las plagas y enfermedades no tuvieron una incidencia reseñable sobre las plantas de tomate durante el primer de cultivo. En el tercer ciclo de cultivo la expresión sintomatológica y mortalidad de las patologías fue similar entre tratamientos y causaron una pérdida promedio de 0,40 kg·m^{-2} [3]. Sin embargo, durante el segundo ciclo de cultivo se manifestó una epidemia de *Botrytis cinerea* de imposible control que provocó una mortalidad media en el invernadero del 40%, obteniéndose en algunas parcelas experimentales una tasa de mortalidad superior al 80%. La epidemia manifestó una mayor agresividad a partir de los 170 DDT. Por ello, la productividad final de la segunda campaña podría estar afectada por la expresión de la micosis. Las mermas de producción ocasionadas solo por *Botrytis cinerea* durante el segundo ciclo de cultivo fueron de 5,27 kg·m^{-2}, a lo cual habría que incorporar las demás plagas y enfermedades que afectaron al cultivo y no se midieron.

Los lodos procedentes del corte del mármol provocaron plantas con un crecimiento deprimido y una productividad menor a las plantas sin incidencia aparente ocho campañas después de su incorporación, donde las productividad final de los tratamientos que no recibieron fertilización inorgánica estuvieron minusvaloradas a causa de esta [3].

En segundo lugar, destacan las deficiencias propias de los métodos analíticos y la influencia de la muestra de suelo sobre los resultados de la investigación, pudiendo tener una influencia elevada sobre las cifras obtenidas.

Rodríguez-Molina [4] ilustró las deficiencias de los métodos clásicos, tomando como referencia los análisis semi-selectivos del género *Fusarium*, siendo extensibles, en cierto modo, a los demás métodos tradicionales. Asimismo, la autora observó una falta de reproducibilidad, repetibilidad y precisión del método, pues influían numerosos factores en él: condiciones experimentales, tiempo de conservación de la muestra, dilución empleada o masa de suelo analizada, analista empleado realizando una misma lectura y muestra estudiada. Estas dificultades y deficiencias son de una fracción microbiológica concreta del suelo, la fusárica.

Asimismo, la muestra de suelo es un factor que puede influir de manera capital en los resultados analíticos y en su precisión [5,6], fundamentalmente por la posible variabilidad espacial de los microorganismos en el suelo y en la muestra [4], lo cual es extensible a las propiedades de físicas y químicas del suelo [7,8]. De esta forma, cabría plantearse la siguiente cuestión: ¿qué muestra de suelo habría que tomar para analizar los parámetros químicos de un suelo? No hay una propuesta representativa para el estudio de la química de un suelo agrícola. En una publicación reciente se propone la siguiente conclusión: "*La variabilidad espacial inherente a las propiedades químicas del suelo a múltiples escalas es difícil de caracterizar, incluso cuando se dispone de importantes recursos para el muestreo y el análisis*…" [9] (página 14). Los autores sugieren que se requiere de un muestreo específico para cada campo agrícola y según las necesidades de cada investigación, debido a que no existe un protocolo de muestreo universal destinado para todos los suelos y nutrientes que sean objeto de medición. En todo caso, recomiendan realizar un muestreo basado en el diseño en vez de en modelos preestablecidos. Esta sugerencia es acorde a los resultados obtenidos por Rodríguez-Molina [4] y Rodríguez-Molina et al. [10] para las diversas especies del género *Fusarium.*

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CONCLUSIONES

1. Conclusiones

A continuación, se muestran las conclusiones obtenidas de esta Tesis Doctoral, a saber:

1. Los resultados obtenidos en el **capítulo I** sugieren que en la agricultura bajo invernadero de la provincia de Almería se producen 1.506,3 kg·m^{-2} de residuos y subproductos plásticos. Los plásticos que envuelven al invernadero, dobles techos y acolchados suponen más del 70% de esta cantidad, y menos de la mitad de las plantas de gestión externas realizan el tratamiento de estos materiales al final de su vida útil.

   Por desgracia, a pesar de los esfuerzos realizados aún se producen vertidos plásticos sobre los espacios naturales del territorio almeriense. Por ello, parece que el actual sistema de gestión no se adapta totalmente a las actuales necesidades del sector.
   No obstante, en el Modelo Almería se identifican diferentes oportunidades para mejorar a dicho sistema bajo el marco de la economía circular. Estas oportunidades pasan por usar los materiales plásticos biodegradables y compostables en aquellos lugares donde se encuentra disponible su uso, mayores campañas de concienciación, el establecimiento de un sistema digital de asesoramiento o implantar un sistema de bonificaciones para fomentar la entrega de los materiales plásticos por parte de la Administración. El interés en esta última medida aumenta aún más si cabe por la relación establecida entre el precio de la materia prima (i.e., barril de petróleo crudo) y el porcentaje de plásticos reciclados en la Unión Europea y sus Estados miembros

2. Los resultados obtenidos en el **capítulo II** sugieren que la fertilización exclusiva a través de reutilizar 3,5 kg·m^{-2} de restos vegetales frescos de tomate del cultivo anterior mediante la técnica de biosolarización obtuvieron una producción final y una calidad del fruto similar a la fertilización inorgánica de cobertera en ciclos de producción de tomate de hasta 217 DDT.

   Además, la microbiota del suelo cultivable tuvo la capacidad de restablecerse al final del ciclo de producción a un nivel similar al detectado antes de aplicar el tratamiento de biodesinfección del suelo, mientras que algunos parámetros fisicoquímicos de relevancia, como la conductividad hidráulica del suelo, nitrógeno total o potasio asimilable; o de vigor vegetal de plántulas hortícolas crecidas en una cámara de ambiente controlado mejoraron con la reutilización reiterada de los restos vegetales frescos de tomate del cultivo anterior.

3. Los resultados obtenidos en el **capítulo III** sugieren que el empleo de enmiendas orgánicas comerciales de alto valor económico (i.e., *pellets* de *Brassica carinata*) pueden reducir significativamente el beneficio económico de un cultivo de tomate en comparación al cultivo convencional y a la fertilización con solo restos vegetales de la campaña anterior a causa de su elevado precio, a pesar de obtener un rendimiento por unidad de superficie similar entre sí.

   La gestión circular de la biomasa agrícola se postula como un método eficaz para dotar a los productores de una batería de herramientas capaces de hacer frente a las demandas internacionales y nacionales de reducir la cantidad de fertilizantes empleados sin mermar el beneficio económico de los agricultores, a la vez que ayuda a reducir el consumo de agua y se mejora la fertilidad de los suelos agrícolas.

APÉNDICES

1. Material suplementario del Capítulo II

Table S1. PERMANOVA analysis of the fungal community in the three years of study (September-April cycles) as a function of crop nutrition.

	Global test		Pairwise test		
Sampling	**Pseudo-F**	***p*-value**	**Treatments**	**t-statistic**	**P(MC)**
Origin	1.6251	0.1147	Test vs IF	1.1502	0.3077
			Test vs PD	1.3067	0.2116
			PD vs Test	1.3463	0.1976
End Season 1	2.552	0.0048	Test vs IF	1.1646	0.2644
			Test vs PD	1.7549	0.0435
			PD vs Test	1.8049	0.0289
End Season 2	4.1707	0.0045	Test vs IF	0.8631	0.5517
			Test vs PD	2.6264	0.0062
			PD vs Test	2.6269	0,0036
End Season 3	1.081	0.3865	Test vs IF	0.6530	0.6829
			Test vs PD	1.1025	0.3253
			PD vs Test	1.3161	0.1938

2. Inorganic fertilization (IF); tomato plant debris (PD); no fertilization (Test).

Table S2. Stepwise linear regression models evaluating the prediction of growth variables of tomato and cucumber seedlings grown in controlled chamber conditions.

	Predicted variable	Adjusted R^2	s^2, df	Predictor variable	β	Partial t test, p-value
Tomato	Nº of leaves	0.112	0.52541, 33	Constant	4.443±0.028	<0.001
				HCO_3^-	-0.064±0.028	0.028
	Height	0.202	0.98328, 33	Constant	1.820±1.321	0.177
				C/N	0.718±0.232	0.004
	Aerial dry weight[1]	-	-	-	-	-
	Roots dry weight	0.276	0.01865, 32	Constant	-0.024±0.027	0.365
				C/N	0.016±0.005	0.002
				Clay	-0.003±0.001	0.016
	Leaf area	0.108	8.25302, 33	Constant	15.128±5.100	0.006
				Nt	127.243±56.168	0.030
Cucumber	Nº of leaves	0.343	0.40582, 33	Constant	2.400+0.808	0.006
				HCO_3^-	-0.071+0.022	0.003
				SOM	0.843±0.357	0.025
				C/N	0.211±0.098	0.039
	Height	0.133	0.38085, 33	Constant	4.213±0.007	<0.001
				Silt	0.018±0.007	0.018
	Aerial dry weight[1]	-	-	-	-	-
	Roots dry weight	0.106	0.01761, 33	Constant	0.023±0.024	0.338
				C/N	0.009±0.004	0.031
	Leaf area	0.249	12.19180, 32	Constant	77.514±16.90	<0.001
				HCO_3^-	-1.815±0.642	0.008
				K+	0.019±0.008	0.022

[1]: Note that a model to predict roots dry weight of tomato seedlings could not be calculated, as none of the variables were selected during the regression

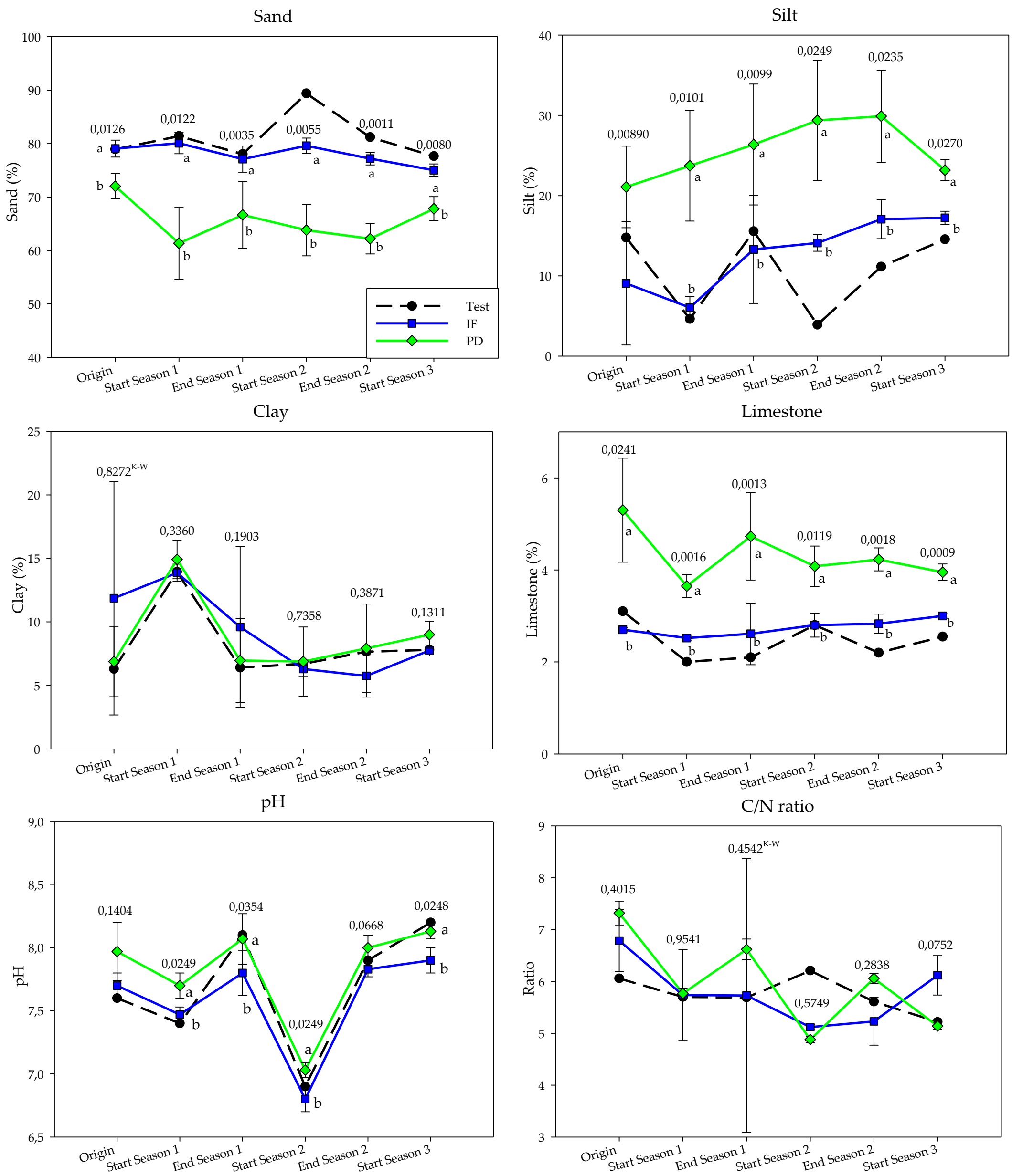

Figure S1. Soil physicochemical parameters in the three years of study (September-April cycles) as a function of crop nutrition. Inorganic fertilization (IF; n=3); tomato plant debris (PD; n=3); no fertilization (Test; n=1). Values (mean ± standard deviation). Different letters indicate significant differences between IF and PD (p≤0.05, Student's t-test; K-W: test Kruskal-Wallis test).

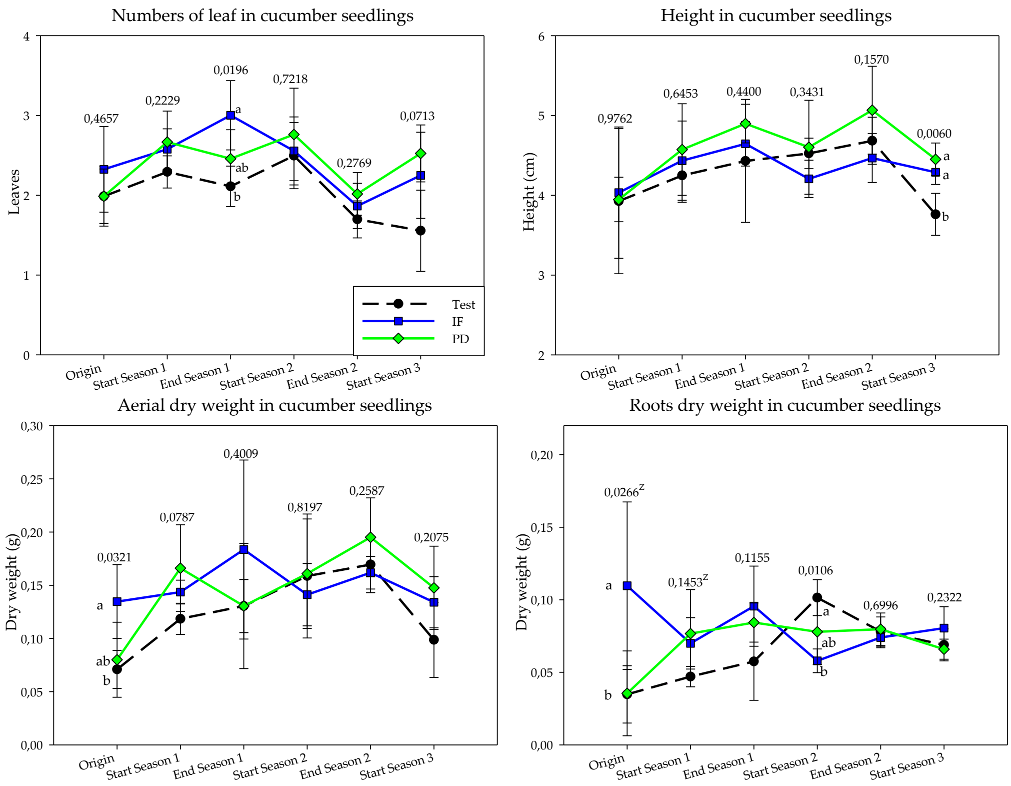

Figure S2. Number of leaves, height and root and aerial dry weight of cucumber seedlings grown in controlled chamber conditions in the three years of study (September-April cycles) as a function of crop nutrition. Tomato. Inorganic fertilization (IF; n=4); tomato plant debris (PD; n=4); no fertilization (Test; n=4). Values (mean ± standard deviation). Different letters indicate significant differences (p≤0.05, Tukey's HDS test; ^{Z}:$\sqrt{x}$).

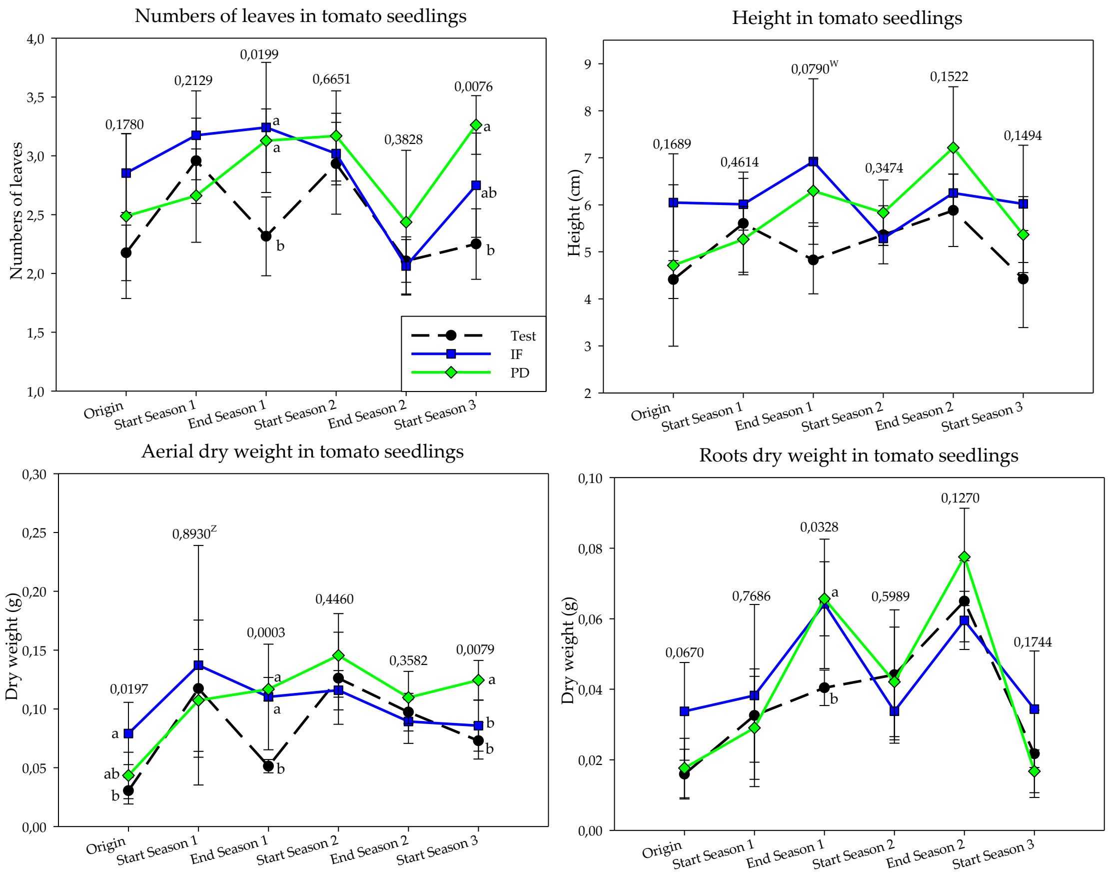

Figure S3. Number of leaves, height and root and aerial dry weight of tomato seedlings grown in controlled chamber conditions in the three years of study (September-April cycles) as a function of crop nutrition. Tomato. Inorganic fertilization (IF; n=4); tomato plant debris (PD; n=4); no fertilization (Test; n=4). Values (mean ± standard deviation). Different letters indicate significant differences (p≤0.05, Tukey's HDS test; ^{W}: $\frac{1}{\log(x)}$; ^{Z}:$\sqrt{x}$).