Food waste-derived biomaterials enriched by biostimulant agents for sustainable horticultural ~~and floricultural~~ practices: a possible circular solution

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Abstract

The horticultural and floricultural industry claims the substitution of plastic plantlet containers, which derive from oil-based raw materials and cannot be recycled, with bio-based ones, aiming to decrease waste management costs and increase the overall production sustainability. Bio-based fully biodegradable nursery pots can be directly placed in soil, thus decreasing the plantlet transplant stress and labor, and avoiding waste generation. The development of biomaterials specifically obtained from food-derived wastes like fruit and vegetables will add further advantages by an improved use of resources, the production of added-value materials and the replenishment of food losses, in a perfect circular economy approach. A multidisciplinary strategy combining material science, microbiology, agronomy and economy will, moreover, allow the development of functionalized food-waste derived materials, enriched in biostimulant extracts, alive plant-growth promoting microorganisms and thermal buffering molecules, obtaining biodegradable and biofertilising plant multiplication plugs with the potential to increase the sustainability of the overall agri-food production chain.

1 Introduction

Over the last decades, several factors had a dramatic impact on the food sector. Growing food demand, food supply chain globalization, agricultural intensification~~Growing world population, globalization of food supply chains, intensification of agriculture~~, and increased ~~affluence~~ wealth of population in ~~large~~ several countries~~groups~~ claimed the need to consider new models of development in this sector, with the goal of achieving a more sustainable economic, environmental, and societal growth (Scarano *et al.*, 2022). Within this scenario, the efficient use of resources and the reduction of food losses and wastes have been identified as the main priorities for the next years and are included among the UN ~~s~~Sustainable 2030 ~~d~~Development ~~g~~Goals Agenda. Accordingly, the transition from a linear to a circular economy model is imperative ~~for~~ in overcoming the problems of food waste and to reach a sustainable resource management (Jõgi and Bhat, 2020).

Among others, the sector of fresh-cut and ready-to-eat fruits and vegetables generates a significant large amounts of organic waste, which represents an evident economic, social, and ethical problem (Campos *et al.*, 2020). At the same time, bio-waste can also be ~~intended as~~ a great opportunity to obtain new resources as added-value products. According to a circular scheme, the~~is~~ organic waste can be profitably used as raw biomass for the generation of functionalized biodegradable materials which could find several applications. One application could be the fabrication of plant nursery plugs used for vegetable production, generating a virtuous circular loop. Today the plant nursery industry largely relies on plugs made of plastic, a non-renewable oil-based raw materials~~The horticulture industry currently largely relies on plastic plugs for plant nursery made of non-renewable oil-based raw materials~~. Plastic plugs are characterized by optimal mechanical properties, chemical, and microbial degradation resistance, durability, as well as low cost but after use in plant nursery they result contaminated by organic matter and chemicals and cannot be properly recycled. To face this problem in the last years alternative plant containers have been developed from a variety of animal- and plant-based renewable sources, including ~~synthetic~~ bioplastics, providing several additional advantages over the thermoplastic containers (Evans, Taylor and Kuehny, 2010; Kratsch *et al.*, 2015).

The development of bio-based and biodegradable plant nursery plugs will certainly intercept multiple needs at different levels: i) the agri-food industry to manage the fruit and vegetable waste material; ii) the bio-based industry to find new green materials while implementing new job opportunities; iii) the horticulture~~/floriculture~~ industry to obtain nursery plant plugs able to improve plantlet yield and productivity, decrease planting labor, and costs related to the plastic plug disposal; iv) the society to decrease both the amount of fossil-derived plastics and the use of chemicals while increasing the food production.

This kind of approach moves in a complex and multi-faceted framework and can be implemented only through a multidisciplinary strategy that requires the integration of ~~several~~different expertise. ~~in~~ ~~m~~Material science plays a pivotal role to select the best agri-food ~~industry~~ wastes and obtain the biopolymers to design biodegradable plant nursery plugs, but other disciplines like microbiology and agronomy can contribute to ~~enrich~~functionalize this innovative product, ~~for instance, with~~by the addition of crop biofertilizers and biostimulants~~and to~~ assessing their efficacy in the field. ~~,~~ ~~agronomy, and~~Lastly but not least, the ~~econom~~economic and life cycle assessment~~y~~ aspects are fundamental ~~related to the production process cannot be overlooked~~to demonstrate the sustainability of the product and its production process.

2 Design of food-waste derived bio-based materials for plant cultivation

The use of biodegradable bio-based pots implies some intrinsic technical advantages over the conventional plastic ones withof petrochemical origin. Plantlet transplant stress is indeed strongly mitigated by the biodegradability of the bio-based plug that permits to place it directly in soil avoiding the plantlet extraction, even by reducing and simplifying the planting labor operations. Transplant stress has been indicated as one of the factors affecting crop productivity (Latimer, Johjima and Harada, 1991), hence its reduction is of great interest for farmers and would contribute to increase the efficiency of plant food production with a consequent more efficient resource use.

Table 1 summarizes the main outcomes of the research works encompassing the production of food waste-derived pots for horticulture and floriculture applications, as a viable and sustainable alternative to conventional containers made by thermoplastic resins. Schettini et al. (2013) performed a study on the mechanical properties, water absorption ability, and biodegradability during pepper plant cultivation in soil using novel bio-based pots consisting of with sodium alginate as the main polymer phase and tomato wastes/hemp fibers as natural structuring disperse phase. Specifically, bio-containers were developed by cold-pressing the formulation inside a pot-shaped molding system. It was demonstrated that the utilization of bio-pots loaded with reinforcing fibers yielded a smooth development of plant roots, accompanied by a good secondary branching structure, thus prompting water and nutrients uptake with respect to that granted by polystyrene-based containers. Moreover, in the same study, the authors observed an overall pot degradation process occurring within 16 days elapsing from the transplanting phase, with roots spreading in a radial mode from the containers to the surrounding soil. Noteworthy, further experiments unveiled a faster biodegradation rate of samples added with tomato skin/seed alone over those also containing an amount of hemp fibers. This behavior was attributed to the food waste-derived fibers which provided a higher contact surface to soil microorganisms and a higher availability of hydroxyl groups standing as attack sites along pectin, starch, and cellulose chains (Schettini *et al.*, 2013).

Fuentes *et al.* (2021) assessed the fertilization ability of several biodegradable pots, as a function of both the utilized structural matrix (e.g., gelatin, wheat/corn waste flour, and cellulose paper) and the solid waste/by-product integrated as filler (e.g., sunflower seed/rice husks, and yerba mate) within the composite material formulation. Corn-waste flour and rice seed husks -derived pots showed poor performances, on the contrary wheat waste flour-based containers loaded with sunflower seed husks exhibited a preventive action towards leaf damages during plant development. As in Schettini et al. (2013) experimentation, the filler particle size demonstrated a pivotal role in explaining such discrepancies, since rice husks particles, being approximately 10-fold greater in size than those belonging to sunflower wastes (0.6 mm), decreased the decomposition rate of bio-pots hampering plant growth.

Commentato [FM1]: @Daniele e Stefano, qui il commento del Revisore 2.
For example, in line 93 the authors mentioned Corn-waste flour and rice seed husks -derived pots showed poor. (Is possible compare in relation to percentage?) I think is possible mention more statistic data in the comparisons.

Santos *et al.* (2017) implemented a suitable strategy to develop thin-walled containers made of biodegradable material, Bioplast GS 2189, classified as a mixture of poly-lactic acid and starch - via injection molding technology. The authors pinpointed the crucial roles played by both the design and/ manufacture of the mold and the tuning of injection parameters to improve process effectiveness and competitiveness. Nonetheless, as emerging from the comparative characterization of pre-processed (grains) and post-processed (biodegradable pots) samples, an incipient degradation effect towards intrinsic properties of materials cannot be excluded, due to the intense shear forces and thermal variations experienced. Even though not including any food waste-derived material within product formulation, the achieved results offered technical guidelines on the proper development of biodegradable pots (Harris, Florkowski and Pennisi, 2020).

Besides the advantages related to material biodegradability, bio-based pots have also the potential to improve plantlet growth. An optimization study of bio-container composition aimed to improve the quality and growth of chili plants throughout the nursery stage was successfully executed by Iriany *et al.* (2020). In this work the effect of water hyacinth petiole (WHP) to coconut coir (CC) mass ratio was investigated on several parameters associated with either plant growth or yield by using a randomized complete block design-based approach, comparing the ~~achieved~~ results achieved with conventional polyethylene plastic pots. Interestingly, the molded bio-pot optimal composition (i.e., 70:30 (w/w) WHP to CC), significantly improved the plant yield parameters ~~as~~ compared with plastic pots, as shown by higher number of fruits per plant and~~,~~ fruit weight (+ 53% on average).

As a general trend, all the reported research works developing bio-based pots (Table 1) demonstrated the positive effect given by the material biodegradability, independently from the intrinsic characteristics (i.e., shape, size) of the food waste employed during bio-pot fabrication, as compared to materials achieved from the processing of bare polymeric substrates alone. ~~Overall, nevertheless, a~~Although most of the researches relied on the molding technology to shape disparate formulations into food waste-based pots, none of them inferred whether the choice of set operative conditions~~, namely temperature, applied pressure, and holding time,~~ would stem from a preliminary optimization study. The latter might have allowed an intensification of the molding process efficiency, with a positive impact on the economic performance of the horticulture and ~~floriculture~~ industry.

Based on these findings, additional efforts are yet to be performed in the direction of overcoming the main limitations associated with the molding technique (e.g., high initial costs, long processing times, poor versatility, among others), in the perspective of industrial scale-up for commercial applications relying on the exploitation of food wastes. In parallel, the use of multiple crop species during in-field performance evaluation might allow to gain more insight into the effect of bio-based materials on crop performance during growth/transplant stages.

3 Novel functionality of bio-based materials for sustainable agriculture

A further innovation of designing bio-based materials is the possibility to enrich and functionalize them using different types of biologically active components, such as biostimulant agents and thermal buffering molecules, to improve plant ~~nursery effectiveness~~growth further increasing the sustainability of the agri-food sector.

Plantlets cultivated in plastic plugs experience a thermal stress due to heat accumulation, a disadvantage that can be overcame by using novel bio-based materials enriched by thermal absorbing particles. Thermal adsorbing particles are based on the phase change material (PCM) technology. PCMs are materials that undergo a phase change, e.g. from solid to liquid state, at a specific temperature (or in a narrow range of temperatures) near the envisaged application. In such systems, energy is stored during melting and recovered during freezing (Li *et al.*, 2009). The latent heat is the thermal energy that needs to be absorbed or released when PCMs change phase and are hence capable to store or release large amounts of energy (Khudhair and Farid, 2004). ~~Because of their great capacity to absorb and slowly release the latent heat, i~~If a PCM is added to a pot inner side, it increases the thermal energy storage capacity of the container (Rentas *et al.*, 2004), representing the most ideal solution for off peak storage (Castell *et al.*, 2011). PCM technology thus represents a powerful approach to mitigate the thermal stress affecting plant nurseries when germination plugs are irradiated and soil temperature rises.

Commentato [FM2]: @Stefano e Daniele, qui il commento del Reviewer 1, cosa intendevate?

l. 119. Please explain better what "positive effect" is in this context (plant growth?). Please rephrase the sentence.

The interest of the market for the use of bioactive compounds ~~for the improvement of~~in crop production is constantly increasing and their production and commercialization have been recently regulated by the European regulation n. 1009/2019, which classified them into two categories: microbial and non-microbial biostimulants. Biostimulants can be obtained from organic matrices of different nature and origin exploiting different extraction processes. Biostimulant molecules can be collected in nature (marine algae, Battacharyya *et al.*, 2015), produced through cultivation (botanical species with a high content of bioactive compounds, Bulgari *et al.*, 2017) or recovered from agro-industrial processes (Xu and Geelen, 2018). The choice of the latter approach would further foster the circularity of the bio-based and biodegradable plug production. Extracts, depending on the organic source and the extraction method applied, have a variable composition with a different concentration of active compounds like minerals, amino acids, sugars, vitamins, antioxidants (polyphenols), plant hormones (Battacharyya *et al.*, 2015; Rodrigues *et al.*, 2020). Plant residuals, such as leaves or flowers of fresh-cut industrial waste, are commonly used as source of bioactive compounds, which can be extracted through maceration in water, using water as a solvent (Franzoni, Bulgari and Ferrante, 2021).

Furthermore, the addition of Plant Growth-~~-~~Promoting Microorganisms (PGPMs) would be extremely interesting to design novel biomaterials for agricultural practices aimed at reducing the use of chemicals, including fertilizers. PGPMs are common members of the plant microbiome able to enhance nutrient bioavailability, promote seed germination and root development through hormone regulation, and protect plants against pathogens as well as abiotic stresses (Rolli *et al.*, 2015; Carrión *et al.*, 2019; Soldan *et al.*, 2019). Overall, they exert a beneficial effect on plant growth, health and production (Riva *et al.*, 2022) and different commercial formulations are available. A bottleneck reducing their effectiveness in the field is the delivery method (Sessitsch, Pfaffenbichler and Mitter, 2019), which strongly impacts the microbial colonization of the root system and the attached soil particles (i.e., rhizosphere). Multiplication plugs made of PGPMs enriched biomaterials can overcome this problem by providing the plant roots with alive PGPMs soon after their emergence from the seed, thus allowing the most favorable conditions for the establishment of beneficial strains.

More researches are ~~is~~ needed ~~for the development~~in order to develop competitive ~~of~~ functionalized biomaterials ~~being competitive with plastic advantages, i.e.~~especially in relation to mechanical properties, chemical and microbial degradation resistance, low cost and durability, the latter especially in relation to the content in alive beneficial microorganisms.

4 Potential impact of bio-based multifunctional materials toward sustainable circular practices in horticulture ~~and floriculture~~

Research activities aimed at developing bio-based multifunctional materials are crucial to deal with the current societal challenges. The design of these materials will contribute to achieve the goals of the UN~~2030~~ ~~United Nation Agenda for~~ Sustainable Development Goals 2030 Agenda (e.g., SDG12 - Ensure sustainable consumption and production patterns). Firstly, they will be obtained recycling organic waste and by-products generated from the food industry, promoting the transition toward a circular economy. Food loss and waste along the food supply chains is given by upstream ~~processes~~ (including production and postharvest) and downstream processes~~ones~~ (including processing, distribution, and consumption). In 2019 food waste reached around 1.3 billion tons annually, with a cost of more than 1000 billion dollars per year (FAO, 2019) and estimates pointed-out that 8-10% of global greenhouse gas emissions ~~a~~were associated with food that is not consumed (UNEP, 2021). ~~All in one t~~This represents a clear economic, environmental and ethical problem that can be solved only by adopting circular economy models.

The obtainment of biodegradable ~~multiplication~~ plugs would be strategic for the horticulture ~~and floriculture~~ sector, considering that the current plugs are largely made of fossil-derived plastic polymers (e.g. polystyrene, polyethylene and polypropylene) thus representing a~~which~~ disposal ~~represents a~~ cost ~~for plant nursery~~. ~~United States data reported that four billion container/plant units are produced by the container crop industry annually, with petroleum-based plastic containers accounting for 1.6 billion pounds of plastic (~~Harris, Florkowski and Pennisi~~,~~ (2020) reported that USA produces four billion container/plant units annually, of which 1.6 billion are petroleum-based plastic containers. Besides fossil resource-independence, further significant advantages of bio-based materials particularly derived from food waste are that they do not compete for resources and land with food production and do not foresee raw material costs (Rosenboom *et al.*, 2022). Life Cycle Assessment (LCA) studies highlighted how the use of plastic materials in the horticultural sector has a non-negligible environmental effect (Lazzerini, Lucchetti and Nicese, 2016) both considering the energy used for plastic manufacturing and the end-of-life of the plastic containers (Schwarzwälde, Estermann and Marini, 2001). The same occurs for bioplastics whose environmental results is controversial, mainly due to the waste management operations (Razza and Cerutti, 2017). In this context, the substitution of plastic pots with bio-based 100% biodegradable materials involves environmental benefits related to the reduction of plastic consumption and the elimination of disposal ~~need~~. Furthermore, the development and adoption of nature-based solutions to increase farm productivity in an environmentally sustainable way is of compelling interest. In this framework, innovative bio-based materials embedding beneficial microorganisms isolated and selected from the plant microbiome, plant waste-derived biostimulants and thermal adsorbing particles would be extremely useful, having the potential to improve plantlet growth and agronomic performance since the nursery stage and limiting physiological stresses related to transplant~~ation~~.

The huge market potential for bio-based materials is confirmed by the European Bioplastic association, estimating an increase in production from around 4.7 million tonnes in 2022 to approximately 7.59 million tonnes in 2026 (https://www.european-bioplastics.org/market/). What is more, the highest growth rate is expected for biodegradable bioplastic compared to bio-based non-biodegradable products (Table 2). The main market driver is represented by the evolution of consumers' demand toward sustainable products: in a recent report, ~~(~~Nielsen~~,~~ (2018) stated that environmentally friendly and recycled packaging are the sustainability attributes that consumers prioritize in their purchasing behaviors. This aspect is of special relevance for European consumers, since the~~a~~ recent Eurobarometer report (2021) revealed that the 78% of respondents feel that environmental issues have an impact on their daily life and health, and almost the 90% are worried about the impact of plastic products ~~o~~in the environment.

5 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 Author Contributions

SB, FM, SF conceived the work. All authors contributed to manuscript writing and editing and approve its content.

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Table 1. Summary of the main preparation techniques adopted to produce biodegradable pots from food wastes.

Food waste	Preparation technique	Main findings	Reference
Grape processing wastes	Mixing of powdered waste with peat and cellulosic fibers, followed by die molding and drying (105°C)	Grape wastes-derived pots showed higher biodegradation rates, as compared to those made by bare lignocellulosic materials	Nechita *et al.* (2010)
Tomato skins/seeds	Mixing (25°C, 30 min) of waste fibers with a sodium alginate aqueous solution (2% w/v), followed by press molding and drying (40°C, 24 h)	Biodegradable pots enabled forming very dense and active root hair, without any shock/root deformation upon transplanting	Schettini *et al.* (2013)
Rice husks	N/A	13% reduction in global warming potential when replacing plastic pots with those based on rice husks	Koeser *et al.* (2014)
	Mixing (25°C, 30 min) of powdered waste with corn-starch/urea-formaldehyde and paraffine wax, followed by hot-pressing (100°C)	Synergistic effect between rice husks and corn-starch in terms of enhanced pot biodegradability	Sun *et al.* (2016)
Coconut coir	Waste-based pots were coated with PLA, polyamide (PA), or polyurethane (PU) by immersion in biopolymeric aqueous or organic solutions, followed by drying (40°C, 2 h)	Plants grown in coated coir-fiber pots were similar in health/size to those grown in petroleum-plastic ones	McCabe *et al.* (2014)
	Mixing of waste with water and hyacinth, followed by molding and drying	Biocontainers produced better growth and yield of chili plants than polyethylene-based bags	Iriany *et al.* (2020)
Corn stovers	Compounding of poly-lactic acid (PLA) with waste (10:90 w/w) and subsequent injection molding	Improved biodegradation of composite material over base PLA	Kratsch *et al.* (2015)
Pineapple wastes	Baking (65°C, 12 h) of ground wastes in the presence of an aqueous tapioca starch solution	Low production costs per pot (0.0075 USD). Pot degradation times greater than 45 days and good water retainability (2 – 3 days)	Jirapornvaree *et al.* (2017)
Wheat straws	Mixing (60°C, 20 min) of waste fibers with hydrolyzed soybean protein isolate/urea-formaldehyde and paraffine wax, followed by hot-pressing	Good thermal stability and mechanical properties, as well as degradability, of fiber-reinforced pots	Sun *et al.* (2018)
		Selective accumulation of bacteria and fungi on pot surface accelerated biodegradation.	Sun *et al.* (2019)
Banana peels	Mixing (25°C, 2 min) of ground waste with tapioca starch, water, and glycerol (until gelification), followed by molding and drying (70°C, 24 h)	Increased microbial decomposition of pots upon banana peel presence within formulation	Rafee *et al.* (2019)
Sunflower seeds	Mixing of ground wastes with either wheat or corn flour aqueous dispersion (1:4 w/w), followed by cold pressing and drying (80°C, 24 h)	Biocontainers behaved as compostable pots, thus fitting nursery growth conditions (frequent irrigation)	Fuentes *et al.* (2021)
Paddy straws	Stirring (90°C, 45 min) of waste with an aqueous solution of native starch and glycerol, followed by press molding and drying (70°C, 12 h)	Mean shoot/root length, and fresh weight of cucumber plant grown in biocomposite pots equivalent to those surrounded by plastic materials	Pratibha *et al.* (2022)

N/A: not available

Table 2. Bioplastic global production (1,000 tonnes): data and forecast. Source: European Bioplastic association.

	2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**Δ 2020-2026**
Biobased/non-biodegradable	848	864	1,025	1,101	1,150	2,140	2,297	+ 170.9%
Biobased/Biodegradable	1,239	1,553	3,694	4,116	4,360	4,583	5,297	**+ 327.5%**
Total	2,087	2,417	4,719	5,217	5,510	6,723	7,594	+ 263.9%