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Customizable and Waste-Free Pharmaceuticals: PLA-Carbon Pills from Biomass Pyrolysis via FDM 3D Printing

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Abstract The pharmaceutical industry is called to adopt more sustainable manufacturing methods to meet current market needs since traditional drug production creates substantial waste while using much energy and failing to meet individualized treatment requirements. This study investigates circular and environmentally friendly methods to create customizable pharmaceutical forms under the framework of 3D-SustainDrugs project. The proposed method uses dual biomass valorization to produce a mixture filament of polylactic acid (PLA) from amylase-rich biomass and carbon from lignocellulosic pyrolysis biochar. The two bio-derived materials form a composite filament which enables Fused Deposition Modeling (FDM) 3D printing of pill platforms. The method enables drug incorporation following printing operations thus protecting the medication from heat exposure while producing customized pill forms for personalized dosing requirements. The combination of carbon with PLA in the filament provides structural benefits, adsorption properties and biodegradable characteristics. The circular economy principles receive support through this approach which connect waste-derived inputs to local free-waste manufacturing operations to achieve Industry 5.0 sustainability goals.

Keywords: Personalized pharmaceuticals; Pyrolysis; Biochar; FDM 3D printing; Circular Economy

1. Introduction

Industrial sectors faces increasing pressure to develop sustainable and resource-efficient practices caused by the immediate need to control global warming and decrease greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report demonstrates that circular and low-carbon systems need to be adopted to fulfill climate targets(Lee et al., 2023). The pharmaceutical industry faces rising environmental criticism because its operations generate substantial waste along with using high amounts of energy and maintaining long inflexible supply networks. This industry also deals with a rising requirement for personalized medicine while its traditional manufacturing systems fail to meet these needs(Ramasamy et al., 2015).

The 3D printing technology is starting to be utilized as an innovative solution to develop personalized medicines while reducing environmental impact in drug production. The Fused Deposition Modeling (FDM) technique allows for individualized production of solid drug formulations through direct manufacturing at the point of need while minimizing waste generation and eliminating the need for central factory-based production systems. This method operates locally while scaling up production by decreasing transportation emissions. At the same time it contributes to reducing unnecessary manufacturing which matches the requirements of green manufacturing principles (Doyle et al., 2020).

The environmental sustainability of 3D-printed pharmaceuticals encounters two main issues which stem from the origins of filament materials and the power usage required during printing processes. Most FDM filaments derive from synthetic polymers yet their manufacturing methods do not fulfill circular economy requirements (Desai* and Krishnamurthy, 2019).

The 3D-SustainDrugs project investigates dual biomass valorization methods to create FDM filaments from waste-derived sustainable materials. The fermentation and polymerization process transforms amylose-containing biomass like potato peels and corn starch into the biodegradable polymer polylactic acid (PLA) while maintaining biocompatibility. Olive pits undergo pyrolysis followed by activation procedures to generate pharmaceutical-grade activated carbon from their carbon content. Two materials serve as components to create specialized FDM printing filaments. The edible and biodegradable pills possess stable structure while maintaining thermal stability and proper gastrointestinal tract dissolution properties. The research investigates the technical practicability and environmental impact alongside social reception of converting waste materials into pharmaceutical products for developing circular and sustainable drug manufacturing practices.

2. Methodology

The research methodology establishes a clear path to integrate agricultural waste for creating customized pharmaceutical pill platforms through FDM 3D printing while maintaining sustainability. The main material, biomass, is separated in two distinct resource-based procedures. The first pathway starts with amylaceous biomass (potato peels and corn starch) that undergoes hydrolysis followed by fermentation using lactic acid-producing bacteria. The purified lactic acid undergoes ring-opening polymerization to create polylactic acid (PLA) before drying and pelletizing for extrusion (Acquavia et al., 2021).

At the same time, the lignocellulosic byproduct olive pits undergo controlled pyrolysis under limited oxygen conditions to produce biochar. The biochar receives physical and chemical activation through steam treatment and acid leaching to boost surface area, porosity and functional group availability which results in pharmaceutical grade activated carbon (Bonelli et al., 2012).

The production of composite filaments occurs through twin-screw extrusion of PLA and activated carbon after drying while maintaining specific weight ratios (e.g., 90:10, 80:20). The evaluation process assesses mechanical strength together with thermal stability and printability and biocompatibility of these filaments. The formulation process targets three main objectives: To achieve optimal structural performance, maintain proper porosity for drug loading and ensure effective dissolution in gastric conditions.

The optimization of filament extrusion parameters enables the preservation of activated carbon porosity alongside PLA melt processability. The composite pellets undergo re-extrusion to create FDM-compatible filaments which are used for printing pill platforms. The combination of porous activated carbon with biodegradable PLA creates structures that are edible and absorbent and dissolve under physiological conditions.

3. Expected Results

The research demonstrates the total conversion of agricultural waste into pharmaceutical materials using FDM 3D printing technology. The research findings will advance material science, pharmaceutical manufacturing and support environmental and societal targets. The research expects the following to be studied and extract results:

i. The main goal is that the PLA–Carbon composite filaments produced by amylaceous biomass and carbon will create edible biodegradable pills through this research.
ii. The research will demonstrate optimized benefits of this filaments regarding its porosity, thermal stability and FDM processing compatibility.
iii. The research will evaluate the drug loading potential of the composite after printing and its dissolution characteristics.
iv. The study will conduct a life cycle assessment (LCA) to evaluate waste-based pills against standard pharmaceutical products and packaging materials while assessing environmental performance and circularity advantages.
v. The research will evaluate public understanding and social acceptance of personalized drugs delivered through edible agricultural waste products.

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