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Innovating pharmaceuticals with sustainable 3D printing for personalized healthcare

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Abstract The pharmaceutical industry significantly contributes to environmental degradation. Traditional drug manufacturing processes generate substantial waste and consume excessive energy, while the industry's one-size-fits-all approach fails to meet the growing demand for personalized treatments. The 3D-SustainDrugs project addresses the pressing need for sustainable practices in pharmaceutical manufacturing by developing a ground-breaking platform for the 3D printing of personalized drug delivery systems. This initiative integrates sustainability principles with advanced digital technologies to optimize the production of non-steroidal anti-inflammatory drugs (NSAIDs). The project targets significant challenges, including the high environmental footprint of pharmaceutical processes and the need for personalized treatments, aiming to reduce waste, energy consumption, and carbon emissions. By focusing on additive manufacturing, green processes, and circular economy principles, 3D-SustainDrugs redefines drug manufacturing to align with the goals of Industry 5.0. A key innovation of the project lies in the production of tailored 3D-printed drug forms, enabling precise dosage personalization and localized manufacturing, which significantly minimizes overproduction and logistical burdens. The project also emphasizes the use of biodegradable and recyclable materials. Through an interdisciplinary collaboration between academic institutions and industry leaders, 3D-SustainDrugs paves the way for a transformative shift in pharmaceutical production, fostering economic viability, environmental stewardship, and healthcare advancement.

Keywords: Sustainable pharmaceuticals; 3D printing technology; personalized medicine; circular economy

1. Introduction

The need for a radical change across all industry sectors to limit Global Warming Potential (GWP) was highlighted in the 6th report of the Intergovernmental Panel on Climate Change (IPCC) (Calvin et al., 2023). Hence, sustainability within the pharmaceutical industry is becoming a focal point for many companies (Weaver et al., 2022).

The production of drugs through 3D printing could contribute to a more sustainable pharmaceutical industry by improving resource efficiency, waste reduction, offering personalized therapies, and enhancing sustainable development. 3D drug printing enables precise and personalized dosage of pharmaceutical preparations, leading reduction in environmental impacts, as production takes place on demand. Moreover, the production of smaller quantities, closer to the point of use, reduces the need for transportation and storage, and therefore reduces fuel consumption and emissions, including CO_2, that occur from transportation. In addition, 3D printing contributes to reducing waste during the manufacturing process through the technique of adding material layer by layer to create the final product, minimizing material loss. The aforementioned is particularly important in the case of NSAIDs, which are used to reduce inflammation in various chronic conditions and are among the most widely used drugs worldwide (Burma et al., 2017).

Among the various 3D printing techniques available today, the Fused Deposition Modeling (FDM) technique is the most widely used in pharmaceutical research applications, mainly due to the availability of low-cost printers and the high printing accuracy (Quodbach et al., 2022). The complexity of printed geometries offers a promising approach to develop solid pharmaceutical forms with controlled drug release profiles and to advance personalized therapies. FDM enables enhanced solubility of pharmaceutical substances while facilitating dose personalization (Dumpa et al., 2021; Roche et al., 2024).

Nevertheless, concerns have been raised regarding some potential negative environmental impacts of FDM printing, such as the release of harmful chemicals during the melting of raw materials and the increased energy consumption of 3D printing (Suárez and Domínguez, 2020). A further concern is the need to develop suitable filaments for feeding the print head during FDM printing, which are primarily produced through Hot Melt Extrusion (Goyanes et al., 2015).

In this light, the 3D-SustainDrugs project aims to apply innovative technological approaches to develop a new

platform for 3D printed personalized NSAID delivery systems. The main objectives of the project are: (i) The development of innovative technological approaches targeting the adoption of sustainable and environmentally viable practices in the 3D printing of pharmaceutical forms, (ii) The optimization of electricity consumption and CO_2 emissions during FDM printing, (iii) The integration of pharmaceutical formulation development and processing into Industry 5.0, and, (iv) The development of a new platform for NSAID pharmaceutical forms using FDM 3D printing.

2. Methodology

The first step of the methodology that will be carried out to achieve the objectives of the project is the development of a database that will include essential data for the execution of the project. The database will serve as the tool for the evaluation and utilization of the results generated throughout the project. Various polymeric filaments will be prepared, which will be evaluated based and their characteristics and properties, and the optimal system will be selected to serve as the feedstock for the FDM printer to produce NSAID Amorphous Solid Dispersions (ASD).

Furthermore, digital models of the pharmaceutical forms will be created, and the critical printing parameters will be determined based on the properties and characteristics of the previously prepared filaments. To confirm the successful development of the ASDs, 3D printing of the pharmaceutical forms will take place, and the solid-state properties will be determined. In vitro dissolution studies will also be conducted on the investigated systems to assess the release profile of the active substance from the developed pharmaceutical systems and to confirm the increased solubility achieved using ASDs. Simultaneously, the project will implement a holistic approach to sustainable development at each stage of pharmaceutical development, identifying parameters that could reduce the process environmental footprint.

3. Expected Results

The expected outcomes of the 3D-SustainDrugs project are: (i) the sustainable development of pharmaceutical products with reduced environmental impacts, (ii) the improved and personalized treatment using NSAIDs, (iii) the creation of new job opportunities, particularly in specialized scientific and research fields, while retaining the existing jobs in both scientific and non-scientific sectors, (iv) the integration of research and innovation into the national industrial framework, with the ultimate goal of curbing “brain drain”, (v) the enhancement of technical expertise among research personnel, and finally, (vi) the exploitation of innovative ideas and technologies developed through the project, which could generate significant economic returns.

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