Development of a bioinformatic platform for the efficient management and biotransformation of agro-industrial waste through microalgae cultivation

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1 Introduction

Food waste, which is defined as any food that is not eaten or waste produced during food preparation in homes or businesses, is becoming a bigger issue in many parts of the world. This problem has important ramifications from an ethical and economic standpoint in addition to an environmental one. There is a huge gap between the effective distribution of food and its production, as evidenced by the fact that so much food is wasted worldwide—enough to feed everyone who is malnourished. Food waste and world hunger are related [1].

The management of food waste is, therefore, a fundamental process to minimise the environmental impact of the waste generated by society. This process involves several stages, such as planning, collection, recycling, processing, and disposal of food waste, to reduce the amount of discarded food and promote its efficient reuse. The implementation of appropriate management practices not only reduces waste but also contributes to sustainability, helping to lessen the pressure on natural resources and the energy required for the production of new food [1].

Given the problems with food waste, creative solutions that not only reduce waste but also enhance the value of the processes' byproducts are desperately needed. In this regard, growing microalgae in agro-industrial waste has become a novel and sustainable way to increase the value of waste from different industries. The cultivation of microalgae is a particularly promising method for adding value to waste, even though techniques like anaerobic digestion, aerobic digestion, and thermal degradation are currently employed. This method provides a circular economy-based solution by producing a range of sustainable goods, including animal feed, pigments, lipids, food supplements, biofuels, and biofertilizers [2].

2 State of the art

2.1 Agro-industrial waste

One of the biggest problems facing the environment and the economy today is food waste. An estimated one-third of the world's food production is wasted, placing a heavy burden on the environment and leading to serious resource inefficiencies [3]. From the stage of cultivation to the point of final consumption, this waste happens at every stage of the production chain, impacting not only the availability of food but also the sustainability of food systems [4].

Agro-industrial waste includes a wider range of by-products than just food-related waste, even though microalgae cultivation has mainly focused on waste from the food industry. Because of its massive volumes and the corresponding negative effects on the environment and the economy, agro-industrial waste is a serious problem. These wastes fall into three primary categories: hazardous wastes, non-recyclable/non-compostable wastes, and recyclable/compostable wastes [5]. For instance, wastes from pits and slaughterhouses are classified as secondary wastes, while recyclable wastes from animal manure and pruning are classified as primary wastes [5]. Hazardous wastes need to be managed strictly in accordance with regulations, and non-recyclable wastes from construction and agricultural mechanisation pose major management challenges [5]. Additionally, many agro-industrial wastes are disposed of by incineration or landfill, leading to environmental and socioeconomic problems [6], and their accumulation exceeds 2 billion tonnes globally, making it imperative to research their utilisation to maximise benefits [7].

The dairy industry is one of the most prominent examples. Whey and wastewater production have significantly increased as a result of the dairy industry's increased production due to rising demand for dairy products [8]. Because they reduce the amount of dissolved oxygen in water bodies, these wastes, which are distinguished by their high organic content, are harmful to the environment. Depending on the product type and operational procedures, dairy wastewater has high concentrations of organic components like lactose, minerals, fat, and whey protein [8].

In addition, the dairy industry contributes significantly to pollution through effluent emissions and waste disposal [9]. This problem is made worse by projections that the global dairy market will reach US$1.243 trillion by 2028, which is predicted to result in an even higher rise in waste production [9]. Although it is one of the biggest polluters, especially when it comes to water consumption, the dairy industry plays a vital role in ensuring the world's food security by turning milk into necessary products [10]. Despite its widespread pollution, the industry has the potential to make a sustainable contribution to global food security [10].

A growing emphasis on the valorisation of waste in the framework of the circular economy is a result of the apparent need for an efficient method of managing food waste. Current strategies encourage resource reduction, recycling, reuse, and recovery in order to maximise material and energy recovery rather than merely eliminating waste [11]. This focus reduces the ecological footprint of food production by enabling the conversion of food waste into useful products like electricity, biofuels, and biofertilizers [11]. But in order for these tactics to work, it is crucial to comprehend the extent of the issue and its root causes, which differ depending on the national context. Only with a comprehensive view of food waste, it will be possible to develop effective policies and solutions tailored to different realities [11].

2.2 Circular economy

The circular economy has been promoted as an effective response to the growing scarcity of natural resources and as a driver for a more sustainable economic system. This approach aims to use resources more efficiently, closing loops and reusing them repeatedly, in order to eliminate the need for virgin raw materials [12]. Furthermore, the circular economy has been widely recognized as a solution to reduce pressure on the environment while simultaneously driving economic growth [13]. However, perspectives on the circular economy are often fueled by imprecise definitions, which hinder a comprehensive understanding of its true application [12].

Although the environmental and economic dimensions of the circular economy are widely discussed, it is crucial to integrate its social dimension for the approach to become truly sustainable. Sustainability is generally recognised as a three-dimensional approach, composed of the economic, environmental, and social dimensions, with the latter often being marginalised in academic discourse [14]. Effectively, a holistic understanding of the circular economy, which takes into account social impacts, is essential to ensure that this approach is not only environmentally efficient but also fair and inclusive for communities [14].

Optimising the social, environmental, technical, and economic values of materials and products in society is essential to restoring and regenerating the environment and realising the full potential of the circular economy. In terms of natural resources and population well-being, this integrative approach can make a substantial contribution to global sustainability [13]. It is crucial to stress that sustainability is not as well incorporated into studies on the topic or into the actual application of the circular economy as it would be ideal. There is a need for more integration of sustainable development principles into discussions and actions related to the circular economy, as evidenced by the fact that only 38% of publications on the topic are in line with these principles cite13.

2.3 Microalgae

Particularly when considering the circular economy and sustainable development, microalgae have become a novel and sustainable solution for a number of industries. Their capacity to develop in a variety of settings and generate useful substances like vitamins, proteins, lipids, and pigments is one of their key advantages. Additionally, because microalgae only require light and basic nutrients and don't require complex compounds or processes, they support the circular economy [15]. An effective method with significant nutritional potential has been found for the cultivation of microalgae using agro-industrial waste, such as that from the processing industries of starches, fruits, vegetables, meat, dairy, olive oil, wine, and beer [1]. This utilization of waste contributes to the valorisation of agro-industrial by-products, reducing waste and providing a sustainable source of biomass.

Microalgae not only play an important role in the generation of biofuels and high-value biocompounds, but also have significant applications in environmental biotechnology, particularly in the treatment of agro-industrial wastewater. This wastewater, often characterised by high concentrations of organic matter, nitrogen, and phosphorus, can cause serious environmental problems if not adequately treated. The cultivation of microalgae can overcome the limitations of other treatment methods, as it promotes the removal of nutrients and the in situ production of oxygen, making it an effective solution for pollution caused by agro-industrial effluents [16].

In terms of sustainable development, microalgae align with the United Nations Sustainable Development Goals (SDGs), contributing to SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production). They provide sustainable sources of food, renewable bioenergy, and high-value biological compounds, assisting in waste remediation and the creation of products such as fertilizers, biogas, proteins, and pigments [15]. Finally, the most common monosaccharides in the polysaccharides of microalgae, such as glucose, galactose, and fructose, are versatile, biodegradable, and biocompatible compounds, with properties that make them suitable for a variety of applications, including the production of chemicals, food, and animal feed [17]. These characteristics highlight the importance of microalgae in the circular economy, which aims to reduce waste and efficiently reuse resources.

3 Objectives

Following the United Nations Sustainable Development Goals 2, 9, and 12, this work plan proposes an innovative approach to reduce the impacts of agro-industrial activities and food retail. The focus is on developing bioprocesses that mitigate and enable the reuse of organic carbon-rich waste, using microalgae. For these processes to be implemented quickly and effectively, it is essential to employ bioinformatics tools that allow for the integration of the most advantageous characteristics of agri-food waste with the identification of microalgae strains with the greatest potential for valorisation of each type of waste.

This study aims to:

1. Create a platform that brings together various agro-industrial waste and by-products, detailing their composition;
2. Incorporate information about the enzymes produced by different species of microalgae on the same platform;
3. Use the platform to identify which by-products can serve as a substrate for the cultivation of microalgae, pointing out the species with the greatest potential for growth in each case.

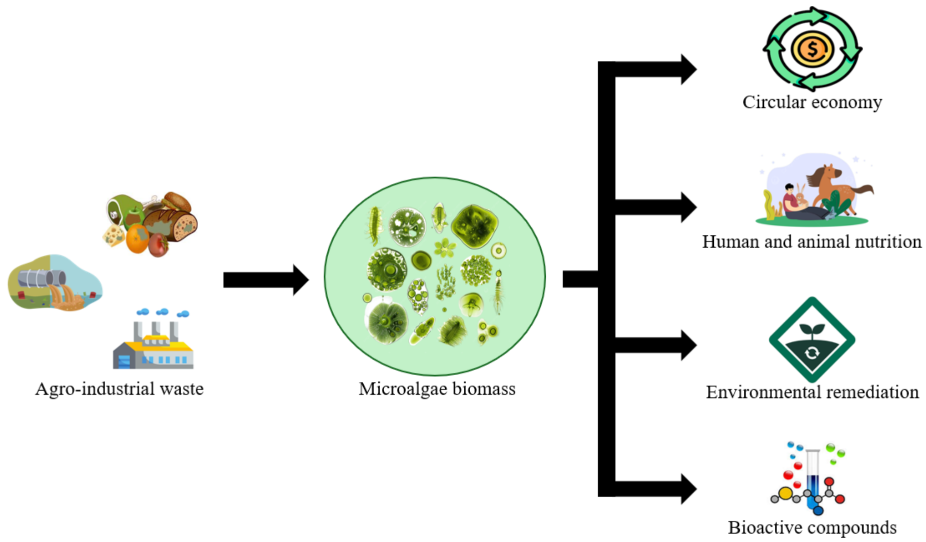

Fig. 1. Schematic representation of the biotechnological valorisation of agro-industrial waste through microalgal biomass production, and its potential applications in circular economy strategies, nutritional supplementation for humans and animals, environmental remediation processes, and the synthesis of bioactive compounds.

4 Methodology

A bioinformatics platform is being developed that initially aims to identify microalgae with genes that encode enzymes capable of degrading sugars such as lactose and sucrose. To achieve this, public databases, such as NCBI, are consulted, using search criteria based on the coding genes of the enzymes of interest. The genetic sequences of these microalgae and the enzymes are obtained in FASTA format, and this data is subsequently processed to compose the database. In the next stage, the set of collected sequences is organized and indexed, associating each microalga with the enzymes it encodes. This mapping is carried out automatically with the help of tools such as BioPython, which allow for the reading and organization of sequences to establish a correspondence between microalgae and the enzymes responsible for the degradation of sugars. The database is complemented by conducting additional queries in sources such as UniProt and KEGG, to obtain more detailed information about the enzymes, including their EC codes, biological functions, and catalyzed reactions, as well as data on the microalgae that produce them. This step enriches the database with relevant information that enables a robust analysis of the data. Finally, a web interface is developed using the Flask framework, which allows the user to enter the name of a sugar and view, in real time, the microalgae associated with the enzymes capable of degrading it. The application's backend performs automatic searches in the database, returning the results in an organized manner and facilitating the identification of microalgae with potential for the biotransformation of waste.

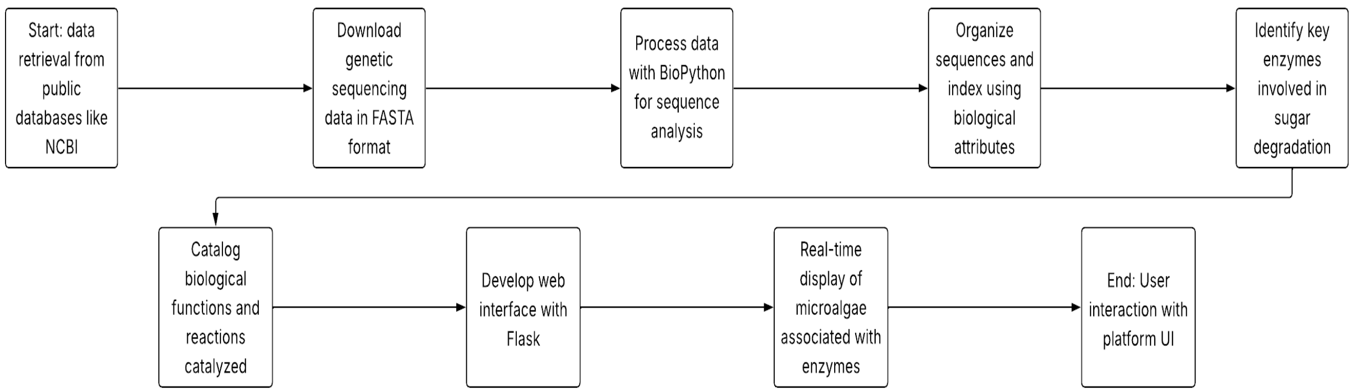

Fig. 2. Flowchart illustrating the stages of acquisition, analysis, and presentation of genetic data from microalgae, from the retrieval of sequences in public databases to the final user interaction with the platform.

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