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Review article

Valorising agricultural waste and by-products for renewable energy: Sustainable technologies and pathways

Emanuele Spizzirri, Mirko Maraldi, Francesca Valenti [*]

Alma Mater Studiorum - University of Bologna, Department of Agricultural and Food Sciences, viale Giuseppe Fanin 50, Bologna 40127, Italy

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ABSTRACT

Technological and industrial development, coupled with global population growth, has led to a rising demand for energy and resources, accompanied by uncontrolled waste production and increasingly severe environmental degradation. The agro-food sector contributes significantly to this issue, generating large amounts of liquid, solid, and gaseous waste, which contain high levels of organic material. Improper management of these wastes exacerbated environmental problems, facilitating the spread of contaminants in soil, air and water. Furthermore, greenhouse gas emissions from agricultural activity contribute to climate change. In alignment with the sustainability goals outlined in the 2015 Paris Agreement, this research aimed to explore ecological and sustainable approaches for managing agricultural waste and agro-industrial by-product. In this paper, a comprehensive literature review is presented. The primary objective of this study was to highlight and discuss the viability of different technologies for the processing of agricultural by-products and waste into valuable products, such as bioenergy, fertilizers or soil improvers. This review encompassed a wide range of technologies, including emerging and innovative methodologies, evaluating their sustainability based on environmental, economic, and social impacts. By synthesizing the latest research and advancements in the field, the review identified critical gaps requiring further investigation and proposed pathways for advancing and implementing these technologies. This was highlighted as an essential step toward the implementation of a circular economy model, where resources are continuously reused and repurposed, contributing to both environmental protection and sustainable development.

1. Introduction

The increasing global energy demand, together with the rising generation of waste driven by population growth, industrialization, and economic development, represents one of the most pressing challenges for contemporary society (Garg et al., 2024; Quevedo-Amador et al., 2024). The difficulties associated with energy demand are further aggravated by the persistent use of fossil fuels, which remain a major driver of environmental degradation and climate change. Recent data indicate that natural gas, coal, and crude oil together still represent close to 80 % of global final energy consumption. Critical sectors such as transportation, agriculture, and industry continue to rely heavily on these non-renewable sources, whose extensive greenhouse gas emissions contribute to ecosystem deterioration and intensify the effects of global climate change (Quevedo-Amador et al., 2024). In particular, rising CO_2 levels alter the way the atmosphere absorbs and releases solar radiation, leading to faster warming and accelerating climate instability (Kumar et al., 2023)

In alignment with the 2015 Paris Agreement, which established the goal of restricting global warming to 1.5 °C, the European Union has reinforced its climate strategy through the European Green Deal. The plan aims to reduce greenhouse gas emissions by 55 % by 2030, compared with 1990 levels, and achieving climate neutrality by 2050. To reach these goals, all sectors need to use more low-carbon practices and expand renewable energy sources, including wind, solar, hydro, geothermal, tidal energy, and biomass (Moura et al., 2022).

Recent work highlights increasing attention from researchers and policymakers toward the use of agricultural residues and by-products as a source for bioenergy generation (Roudneshin and Sosa, 2024; Ufitikirezi et al., 2024; Niyogi et al., 2024). Agricultural activities produce vast amounts of residues, ranging from crop remains to agro-industrial by-products (Garg et al., 2024). Over the past decades, the continuous accumulation of organic biomass has contributed to significant environmental pressures, while simultaneously resulting in the loss of

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[*] Corresponding author.
E-mail address: francesca.valenti9@unibo.it (F. Valenti).

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resources that could otherwise be valorised for energy or other high-value applications (Aravind Kumar et al., 2022). According to Ufitikirezi et al. (2024), agricultural residues can be broadly classified into several main groups: crop-derived materials such as stems, leaves, roots, husks, and peels; industrial by-products from the processing of plant and animal commodities, including those from the food sector; livestock-related wastes such as manure, bedding, carcasses, and effluents; and food waste, referring to edible fractions discarded at different stages along the supply chain.

Recent studies highlight those industries are progressively acknowledging the economic and strategic potential of agricultural residues and by-products. These biomasses, abundant and renewable, can be transformed into multiple energy carriers, such as biogas, biodiesel, bioethanol, and even bioelectricity, offering both an effective route for sustainable waste management and a significant contribution to renewable energy generation (Garg et al., 2024; Ufitikirezi et al., 2024; Sharma, 2024).

Furthermore, converting agricultural residues into bioenergy is consistent with the principles of the circular economy, where waste streams are reinterpreted as valuable resources that can be harnessed for energy and other benefits (Niyogi et al., 2024; Sharma, 2024; Garg et al., 2024; Ufitikirezi et al., 2024), including the recovery of essential nutrients such as carbon, nitrogen and phosphorus (Nguyen et al., 2021). Utilizing agricultural biomass can play a key role in enhancing energy reliability, broadening the diversity of energy sources, and fostering rural economic development (Garg et al., 2024; Ali et al., 2024). Nevertheless, adopting bioenergy pathways requires a sustainability-oriented approach, so that energy generation does not undermine crop productivity nor trigger competition over land use (Ali et al., 2024). Achieving this goal demands, a thorough evaluation of available biomass feedstocks and conversion pathways, with explicit attention to environmental, economic, and social sustainability aspects (Roudneshin and Sosa, 2024).

Biomass can be used in many sectors, such as heating, power production, and transport, but its wide variation in origin and composition creates several challenges—from collection and sorting to conversion efficiency. Improving pre-treatment methods, especially for lignocellulosic materials, is important for increasing energy yields and lowering production costs. The characteristics of each feedstock play a key role in deciding which conversion process is most appropriate and what type of bioenergy can be obtained. In this context, biofuels are commonly grouped as primary (unprocessed materials like firewood or pellets) and secondary, which are further divided into first through fourth generations depending on the feedstock and technology applied. Nonetheless, no universally accepted classification exists, as categories may shift depending on the purpose and scope of the analysis (Banerjee, 2023). The division of biofuels into four successive generations offers a useful framework to trace the technological development of biomass conversion routes towards renewable energy (Ali et al., 2024; Garg et al., 2024).

While previous reviews have explored biomass-to-energy technologies (Ali et al., 2024; Banerjee, 2023; Quevedo-Amador et al., 2024), many concentrate on particular conversion pathways, feedstock categories, or biofuel generations, often paying limited attention to pre-treatment requirements or novel strategies. To overcome these gaps, the present systematic review delivers an integrated overview of sustainable technologies for renewable bioenergy generation, with specific emphasis on the pre-treatment of agricultural residues and by-products. The review is structured around the four generations of biofuels, each reflecting specific technological developments and sustainability aspects. Particular focus is given to pre-treatment, since it plays a key role in improving conversion efficiency but is often not fully addressed in previous studies. Each generation is discussed by considering technical, environmental, economic, and social aspects, outlining both the main benefits and the limitations that still hinder wider commercial application. By adopting a comparative and multidimensional perspective, the analysis identifies context-sensitive strategies for implementing the most suitable bioenergy technologies in relation to locally available resources. Ultimately, the work seeks to equip stakeholders—from policymakers to industry actors—with evidence-based insights on how sustainable bioenergy can underpin a circular economy and support a climate-resilient energy transition.

2. Methodology

This Systematic Literature Review (SLR) was conducted following the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2015), with the aim of identifying, selecting, and critically analysing the scientific literature related to green technologies available for the recovery of bioenergy from agricultural by-products and waste.

The literature search was carried out using the Scopus and Web of Science databases, covering records published between 2013 and 2024 and limited to English-language publications. No restrictions were applied regarding document type at the search stage, in order to ensure broad coverage of the literature. A structured search string was developed using Boolean operators (AND, OR) to ensure the retrieval of the most relevant documents. The Boolean search string used on Scopus was:

TITLE-ABS-KEY (sustainable AND technology AND bioenergy AND byproduct OR (agricultural AND waste)).

The corresponding search string used in Web of Science was:

(TI=(sustainable) OR AB= (sustainable) OR AK= (sustainable) OR KP= (sustainable)) AND (TI=(technology) OR AB= (technology) OR AK= (technology) OR KP= (technology)) AND (TI=(bioenergy) OR AB= (bioenergy) OR AK= (bioenergy) OR KP= (bioenergy)) AND ((TI= (byproduct) OR AB= (byproduct) OR AK= (byproduct) OR KP= (byproduct)) OR (TI=(agricultural waste) OR AB= (agricultural waste) OR AK= (agricultural waste) OR KP= (agricultural waste))).

It is important to note that the two search strings are not perfectly aligned due to differences in database indexing: for example, the term KEY in Scopus also includes INDEXTERMS, which are *"Controlled vocabulary terms assigned to documents"*.

The selection of the studies describes and analyses sustainable technologies for the production or recovery of bioenergy from agricultural matrices. After removing duplicates, titles and abstracts were manually screened to exclude studies that did not address bioenergy technologies or were unrelated to agricultural biomass. The remaining records underwent full-text assessment to verify their relevance to the objectives of the review. The number of records included and excluded at each step was systematically documented.

The literature search retrieved a total of 359 records: 319 from Scopus and 140 from Web of Science. After removing 109 duplicates, 350 unique articles remained and were screened based on their titles and abstracts. This screening led to the exclusion of 256 records that did not meet the inclusion criteria, leaving 94 articles for full-text reading. At this step, 63 papers were excluded for not meeting the inclusion criteria, leaving 31 studies for the final review. We also complemented the database search with a manual check of the reference lists (backward snowballing) to find any additional relevant publications.

This approach allowed for an expanded evidence base, including publications that, although not directly retrieved through the keyword search, were closely aligned with the objectives of the review.

Using this methodology, 4 more articles were added, for a total of 35. The overall methodology adopted for the SLR is summarized in the flowchart presented in Fig. 1.

A structured data extraction approach was applied to all studies selected after the full-text screening. For each article, information was collected on the type of agricultural residue, by-product, or waste examined, the pre-treatment strategy adopted, and the conversion process described. Particular attention was also given to the technological performance reported and any environmental, economic, or social

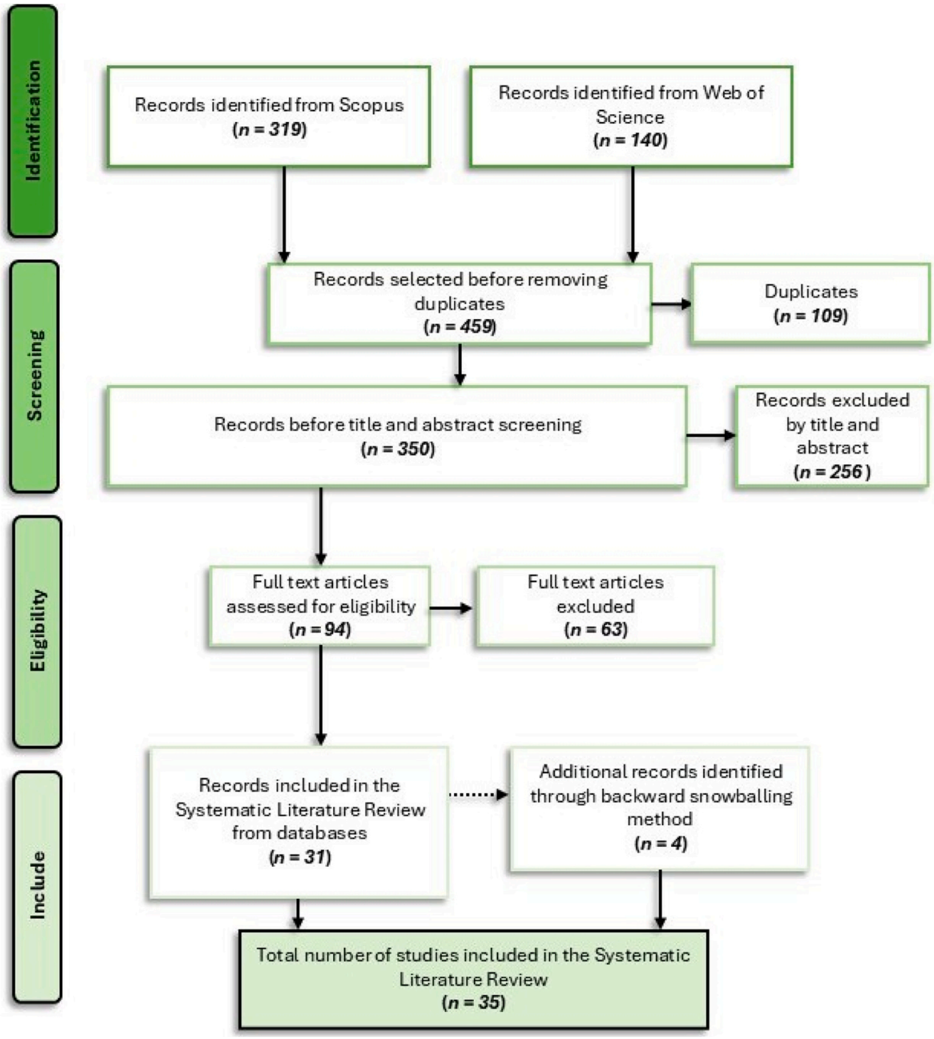

Fig. 1. – Flowchart of the SLR methodology.

sustainability indicators. This systematic approach made it possible to compare the evidence reported in the selected papers in a consistent way. While no formal scoring system was used, a study was included only if it described its methods clearly enough to understand the conversion steps and the resulting technological outcomes. Papers that did not provide this minimum level of detail were removed during the full-text evaluation.

The review was then organised into three main parts: biomass types (Section 3), with particular attention to agricultural residues and by-products; pre-treatment methods (Section 4), which are central to improving conversion efficiency; and sustainable technologies for bioenergy recovery (Section 5), grouped into four generations that range from established to emerging pathways. In this way, the review aims to provide a comprehensive understanding of the current state and future potential of sustainable technologies for renewable energy production from agricultural residues and by-products.

3. Biomass classification

Biomass constitutes a versatile feedstock that can be transformed into a variety of renewable energy forms—including heat, power, and biofuels—through different conversion technologies. The composition of biomass is largely defined by its structural polymers—such as cellulose, hemicellulose, lignin, starch, and proteins—but it can also contain extraneous fractions including lipids and ash, which further influence its conversion potential (Pallath et al., 2024; Adnane et al., 2024). Biomass is highly variable: moisture level, ash content, and the lignin–cellulose ratio can change a lot from one feedstock to another. Such traits influence energy yield, conversion performance, and the sustainability of the process (Banerjee, 2023; Kag et al., 2022).

For this reason, the following section reviews the main biomass categories used in bioenergy production, highlighting their key physicochemical features and outlining the strengths and limitations linked to each type. A detailed understanding of these aspects is essential for tailoring pre-treatments, optimizing conversion technologies, and advancing efficient and sustainable bioenergy production.

3.1. *Types of biomasses*

As outlined by Santhakumari et al. (2024), biomass can be classified into several categories according to its origin and chemical constitution. Another widely used approach considers the feedstock source, the type of vegetation, as well as its intended use and applications (Banerjee, 2023). The following subsections present the main biomass types currently exploited for bioenergy production:

3.1.1. *Lignocellulosic biomass*

Lignocellulosic biomass, the most widespread form of biomass globally, consists predominantly of cellulose, hemicellulose, and lignin (Kag et al., 2022; Quevedo-Amador et al., 2024). Typical sources include agricultural residues such as cereal straw, corn stover, and sugarcane bagasse; forestry by-products like wood-processing waste and branches; non-food energy crops; and selected fractions of municipal solid waste (Ali et al., 2024). Owing to its high content of structural carbohydrates, it is regarded as a valuable feedstock for liquid biofuels, especially bioethanol (Pandiyan et al., 2019). Despite this potential, its complex structure poses notable barriers: the crystalline organization of cellulose and the recalcitrance of lignin hinder enzymatic and catalytic access, making intensive and costly pre-treatment steps indispensable (Kag et al., 2022; Adnane et al., 2024). Moreover, certain pre-treatment methods generate inhibitory compounds that can impair biological processes such as fermentation. The development of eco-friendly and energy-saving pre-treatment strategies is therefore essential to reduce the environmental footprint associated with conventional lignocellulosic processing (Kag et al., 2022).

3.1.2. Sugar- and starch-rich biomass

Sugarcane, sugar beet, cereals, and tuber crops are typically grouped under the category of sugar- and starch-rich biomasses (Santhakumari et al., 2024). These feedstocks are characterized by a high content of readily available carbohydrates, either in the form of simple sugars (mono- and disaccharides) or starch, a polysaccharide that can be hydrolysed into fermentable sugars. Thanks to their composition, these crops can be converted into bioethanol efficiently and typically provide high fermentation yields (Santhakumari et al., 2024). However, the use of food crops like corn and sugarcane for energy raises concerns about food security and possible food price increases (Banerjee, 2023). In addition, their intensive cultivation also brings environmental pressures, linked to the large-scale application of fertilizers, pesticides, and land resources (Ali et al., 2024; Banerjee, 2023).

3.1.3. Oil-rich biomass

Oil-rich feedstocks comprise oilseeds—including soybean, rapeseed, sunflower, and palm—as well as micro- and macroalgae (Santhakumari et al., 2024). The lipids extracted from these biomasses can be transformed into biodiesel via transesterification. Among them, algae stand out as highly productive candidates for biodiesel generation, with the additional advantage of not competing with food crops for arable land (Ali et al., 2024). Large-scale algal systems demand substantial inputs of water and nutrients and significant energy for drying, raising concerns about their environmental footprint (Banerjee, 2023).

3.1.4. Organic waste (wet waste)

Organic or wet biomass includes streams such as food residues, animal manure, and sewage sludge (Ali et al., 2024). Due to their high moisture content, these materials are particularly suited to biological conversion routes, especially anaerobic digestion, which generates biogas composed mainly of methane (Ali et al., 2024; Adetunji, Oberholster, e Erasmus, 2023). Manure alone, however, is characterized by a low carbon-to-nitrogen (C/N) ratio, which can hinder microbial activity and digestion efficiency by increasing alkalinity. Co-digestion with lignocellulosic substrates provides a more balanced C/N ratio and mitigates ammonia-related inhibition (Ali et al., 2024; Adnane et al., 2024). In addition to energy recovery, anaerobic digestion of organic waste contributes to reducing landfill disposal volumes (Banerjee, 2023; Sharma et al., 2023). The digestate generated as a by-product can be applied as an organic fertilizer, closing nutrient cycles (Ali et al., 2024). Nevertheless, the heterogeneous composition of organic waste may compromise process stability and efficiency, and in some cases, pre-treatment is required to improve biodegradability and reduce the environmental footprint of the digestate (Adnane et al., 2024).

3.1.5. Woody biomass

Woody biomass, which comprises forest resources such as trees, shrubs, and by-products of wood processing, represents the most widely exploited source of bioenergy. Traditionally, it has been burned directly, mainly to provide heat and support domestic cooking. (Banerjee, 2023). Besides its traditional uses, this type of biomass can be processed through thermochemical routes such as gasification and pyrolysis, which make it possible to obtain syngas and bio-oil. (Pallath et al., 2024; Banerjee, 2023). The long-term sustainability of this resource depends heavily on good forest management, as unsustainable practices can cause deforestation, soil degradation, and biodiversity decline (Ali et al., 2024).

3.2. Physicochemical characteristics of biomasses

The physicochemical traits of biomass are decisive in assessing its suitability for different bioenergy conversion routes (Niyogi et al., 2024). These properties affect both the ease of processing and the efficiency and quality of the final energy products (Banerjee, 2023). The elemental composition—mainly carbon, hydrogen, oxygen, nitrogen, and sulphur—and the distribution of macromolecules such as cellulose, hemicellulose, lignin, starch, sugars, proteins, and lipids vary widely among feedstocks (Kag et al., 2022; Santhakumari et al., 2024). For example, lignocellulosic biomass is rich in structural carbohydrates and lignin, while oilseed crops contain large amounts of triglycerides, leading to different conversion options. The ratio between cellulose and lignin is an important aspect: when cellulose is high compared with lignin, biochemical conversion is generally easier because less lignin needs to be removed (Banerjee, 2023). Moisture is another key factor. High water content reduces the efficiency of thermochemical pathways such as combustion and gasification, making drying steps necessary, while it can favour aqueous-phase processes such as fermentation, as in the case of sugarcane (Banerjee, 2023). Ashes, the inorganic residues left after combustion, influence fuel yield and reactor performance, and their composition varies depending on the biomass source (Santhakumari et al., 2024; Banerjee, 2023). Energy potential is also assessed through calorific values (higher or lower heating value), while physical attributes such as bulk and energy density (Alakangas, 2016) determine handling, storage, and reactivity (Banerjee, 2023). Combustion characteristics can also be linked to the ratio between fixed carbon and volatile matter: lower values usually indicate that the material ignites more easily (Banerjee, 2023). For lignocellulosic biomass, cellulose crystallinity and the degree of polymerization are crucial: higher levels make the material more resistant to enzymatic hydrolysis (Pandiyan et al., 2019). In addition, high concentrations of alkali metals can promote fouling and corrosion in thermochemical systems (Banerjee, 2023). For these reasons, detailed biomass characterization, combining proximate analysis (moisture, ash, volatile matter, fixed carbon) with elemental analysis (C, H, O, N, S), is essential to match each feedstock with the most suitable conversion pathway and to optimise overall process performance.

4. Pre-treatments

In their natural state, biomass display a complex organization and an intrinsic recalcitrance that limit the efficiency of conversion processes (Kag et al., 2022). Lignocellulosic materials, in particular—mainly composed of cellulose, hemicellulose, and lignin (Pallath et al., 2024)—are especially resistant and therefore require preliminary steps, commonly referred to as pre-treatments, which are intended to weaken these barriers and improve energy recovery (Pandiyan et al., 2019). This section examines pre-treatment approaches that are fundamental to enabling sustainable conversion technologies, improving process performance, and fostering the production of bioenergy and related bioproducts.

The rigid architecture of lignocellulosic biomass restricts enzymatic hydrolysis by reducing the accessibility of cellulose and hemicellulose, which represent key substrates for the production of liquid biofuels such as bioethanol. Lignin plays a central role in this limitation: due to its complex composition and strong interactions with carbohydrates, it functions as both a physical and chemical barrier that hinders biological and thermochemical transformations (Kag et al., 2022). In addition, factors such as cellulose crystallinity, the degree of polymerization, and the limited surface area available for enzymatic attack further lower hydrolysis efficiency (Pandiyan et al., 2019).

For these reasons, the development of effective pre-treatment strategies is essential to improve biomass conversion, enhance the competitiveness of sustainable technologies, and enable their adoption on an industrial scale (Sharma, 2024). The overarching aim of pre-treatment is to modify the physicochemical properties of biomass in order to facilitate subsequent steps in the conversion chain (Adnane et al., 2024; Pandiyan et al., 2019). These steps help make the material easier to process by opening up its structure, increasing surface area, disrupting the lignin network, and lowering the crystallinity of cellulose. At the same time, it is essential to preserve fermentable sugars and prevent their breakdown, so as to avoid the formation of inhibitory compounds that can limit the activity of microbes or catalysts. Reducing energy use and keeping processing costs under control are equally important. Taken together, these aspects are key to achieving high conversion yields and to making biomass technologies both sustainable and economically feasible.

4.1. *Classification of pre-treatment methods*

According to Pallath et al. (2024), pre-treatment technologies for biomass are commonly grouped according to their main operating principle, and are generally distinguished as physical, chemical, biological, or integrated hybrid approaches.

4.1.1. *Physical methods*

Physical pre-treatment methods are designed to fragment biomass into smaller particles and increase its surface exposure by applying mechanical forces (Kag et al., 2022). Conventional operations such as milling and grinding reduce particle size and are known to enhance anaerobic digestibility as well as enzymatic hydrolysis (Kag et al., 2022; Adnane et al., 2024). Extrusion, another widely used technique, couples shear stress with heat and pressure, thereby disrupting biomass structure and improving its processability; when combined with chemical agents, it can further increase conversion efficiency (Kag et al., 2022; Kang et al., 2022; Adnane et al., 2024).

Several advanced approaches have also been investigated. Pulsed electric field (PEF) technology applies high-voltage discharges that perforate cell membranes, facilitating the recovery of valuable compounds from residues such as fruit, vegetable, and animal by-products. This method is regarded as relatively sustainable and energy-efficient, and is often integrated with other processes to improve the extraction of bioproducts (Sagar et al., 2024). Microwave irradiation uses electromagnetic waves to heat biomass in the internal part, causing structural disruption and promoting carbohydrate release (Kag et al., 2022; Kang et al., 2022). Ultrasonication, which relies on high-frequency acoustic waves, disrupts cell walls and enhances solubilization, hydrolysis, and methane production—effects that are further amplified when combined with electrolysis in algal biomass processing (Adnane et al., 2024; Kag et al., 2022; Sagar et al., 2024). Among thermophysical pre-treatment methods, steam explosion is one of the most widely applied: high-temperature pressurized steam for a short period and then rapidly depressurized, a process that promotes hemicellulose solubilization and alters the lignin–cellulose matrix (Adnane et al., 2024; Kang et al., 2022). Equally, liquid hot water (LHW) pre-treatment relies on water maintained under high temperature and pressure in liquid form; this promotes ion dissociation and the generation of organic acids, which drive the depolymerization of hemicellulose into fermentable sugars (Adnane et al., 2024; Kang et al., 2022).

4.1.2. *Chemical methods*

Chemical pre-treatments employ a variety of reagents to modify the composition and structural integrity of biomass, thereby improving its suitability for conversion (Kang et al., 2022). Acid-based strategies, which can rely on either dilute or concentrated organic and inorganic acids, primarily hydrolyse hemicellulose and enhance cellulose porosity. However, these processes often lead to the formation of inhibitory compounds such as phenolic acids and aldehydes (Adnane et al., 2024; Kag et al., 2022). Alkaline pre-treatments are also widely applied, in which bases such as sodium hydroxide or potassium hydroxide are used to delignify biomass and disrupt ester bonds between lignin and carbohydrates. This increases cellulose digestibility, though it generally requires longer reaction times and produces alkaline effluents that must be managed appropriately (Adnane et al., 2024; Kag et al., 2022; Kang et al., 2022). The organosolv method employs organic solvents, typically ethanol, methanol, or acetone, combined with heat and pressure, to selectively dissolve lignin and produce more purified fractions of cellulose and lignin (Kag et al., 2022; Kang et al., 2022). Ionic liquid pre-treatment, in contrast, uses salts with low melting points that are capable of dissolving lignocellulosic material almost completely, enabling fractionation of its main components (Santhakumari et al., 2024). While effective, this approach is costly and depends heavily on solvent recovery and recycling to remain sustainable (Kag et al., 2022; Santhakumari et al., 2024). Other chemical strategies include ozonolysis, which applies ozone to degrade lignin and hemicellulose (Kag et al., 2022), and the Ammonia Fiber Expansion (AFEX) process, where biomass is treated with liquid ammonia under high temperature and pressure followed by rapid release, thereby altering lignin structure and improving cellulose accessibility (Kang et al., 2022).

4.1.3. *Biological methods*

Biological pre-treatments rely on microorganisms or enzymes to deconstruct the complex matrix of biomass under relatively mild operating conditions, resulting in lower energy demand and fewer inhibitory by-products compared with other approaches (Kang et al., 2022). Among the most widely studied strategies is fungal treatment, which employs lignin-degrading fungi—including white-rot, brown-rot, and soft-rot species—to selectively break down lignin and hemicellulose. This enhances cellulose accessibility through the action of extracellular oxidative enzymes such as laccases and peroxidases (Kang et al., 2022). Another important approach is enzymatic pre-treatment, in which specific enzymes (e.g., *cellulases, hemicellulases, and ligninases*) are used to hydrolyse structural polymers of the biomass. This method has been shown to improve methane production and can be adapted for microalgae, either with single enzymes or cocktails, depending on the intended product—biogas, biohydrogen, or lipid extraction for biodiesel (Zabed et al., 2019). While highly specific and environmentally friendly, the high cost of enzymes remains a major limitation (Kang et al., 2022). The use of microbial consortia (MCons) is also attracting growing attention. These communities of microorganisms exhibit diverse enzymatic activities that act synergistically, enabling more comprehensive degradation of lignocellulosic residues as well as microalgae. Such systems are promising because they can hydrolyse recalcitrant fractions and secrete a wide array of extracellular enzymes (Adnane et al., 2024; Zabed et al., 2019). Finally, ensiling represents a biological pre-treatment based on lactic acid fermentation in solid-state conditions. Besides preserving biomass, it modifies its composition in ways that enhance digestibility and facilitate subsequent anaerobic digestion, thereby improving the overall bioenergy yield (Adnane et al., 2024; Zabed et al., 2019).

4.1.4. *Other pre-treatment techniques*

Beyond the conventional categories, several additional processes can act as effective pre-treatments when applied under specific operational conditions. A possible option is the use of Supercritical Fluid pre-treatment (SF), where a fluid is maintained above its critical pressure and temperature and therefore exhibits hybrid properties of gases and liquids, such as density and compressibility. Among the different fluids tested, carbon dioxide is most commonly applied because it combines effectiveness with operational safety. When biomass is treated with carbon dioxide in a pressurized reactor, the cellulose matrix undergoes partial disintegration, which enlarges its accessible surface area and promotes enzymatic hydrolysis, ultimately enhancing fermentable sugar recovery (Kag et al., 2022). A different approach is torrefaction, a thermochemical upgrading step in which biomass is exposed to an inert atmosphere at intermediate temperatures, typically 200–300 °C. This mild pyrolysis process modifies several drawbacks of raw feedstocks, including high water content, heterogeneity, and low energy density. The solid fraction obtained—commonly referred to as "biocoal" —is characterized by a drastic reduction in residual moisture (around 3 % by weight) and by notable improvements in calorific value and fixed carbon content (about 15–25 % higher than untreated biomass). These changes make torrefied biomass more stable, easier to handle, and generally more suitable as a renewable solid fuel (Negi et al., 2020). Finally, hybrid strategies that combine multiple pre-treatments are increasingly adopted. For example, mechanical size reduction can be carried out before chemical or enzymatic treatments, improving reagent penetration and lowering chemical demand. When different methods are used together, they often produce complementary effects, shortening processing times, lowering costs, and increasing the overall efficiency of lignocellulosic conversion (Kang et al., 2022).

5. Sustainable biofuel technologies

Renewable biomass feedstocks comprise a wide array of resources, including agricultural crops, energy-dedicated plants, urban and wet wastes, as well as algal derivatives. Even landfill waste can be harnessed to generate renewable energy. Examples of such raw materials include maize grains and stover, soybean and canola oils, animal-derived fats, woody biomass, and algae, all of which are recognized as consistent energy sources (Ali et al., 2024). To differentiate between the types of feedstocks and the conversion pathways used, the concept of "biofuel generations" is often applied. This framework allows for a systematic evaluation of the sustainability, efficiency, and environmental consequences of biofuel technologies. In this review, biofuels are categorized according to four main generations: (i) first-generation biofuels, which are obtained from edible crops such as maize, sugarcane, and oilseeds (Banerjee, 2023); (ii) second-generation biofuels, based on non-food lignocellulosic resources, including agricultural and forestry residues or non-dedicated energy crops (Banerjee, 2023); (iii) third-generation biofuels, produced from microalgae and other aquatic microorganisms (Banerjee, 2023); and (iv) fourth-generation biofuels, which rely on advanced biotechnology and genetic engineering of microorganisms to achieve superior yields and properties (Ali et al., 2024).

5.1. *First-generation biofuels (1 G)*

First-generation biofuels are derived from edible crop biomass, and two main technological routes dominate their production. The first is alcoholic fermentation, in which sugar-rich feedstocks such as sugarcane are processed to obtain bioethanol (Kag et al., 2022; Pandiyan et al., 2019). In this pathway, microorganisms like yeasts convert fermentable sugars into ethanol and carbon dioxide under anaerobic conditions. A critical step in this process is enzymatic hydrolysis, which converts complex carbohydrates into simpler sugars that can be fermented (Fagundes et al., 2024). Despite its effectiveness, dependence on food crops for this purpose raises sustainability concerns, particularly in relation to food security and land-use competition (Ali et al., 2024). The second main pathway is transesterification, where vegetable oils (e.g., soybean or canola) and animal fats are converted into biodiesel (Ali et al., 2024; Bhatia, Joo, and Yang, 2018) using alcohols such as methanol or ethanol in the presence of a catalyst. This reaction produces fatty acid esters, the main component of biodiesel, along with glycerol as a by-product The method is widely adopted because it can accommodate a range of lipid feedstocks and catalysts, operates under relatively mild conditions, and provides high conversion efficiencies (Bhatia, Joo, and Yang, 2018; Quevedo-Amador et al., 2024). First-generation biofuels remain the most mature option from a technological point of view, as the related processes are widely commercialized and contribute significantly to global biofuel production (approximately 50 billion litres per year). Their economic appeal comes from relatively simple conversion routes and well-developed supply chains. Environmentally, these 1 G fuels can also lead to notable cuts in greenhouse gas emissions, often estimated at 45–65 % compared with fossil fuels. Their sustainability, however, is limited by several socio-economic issues (Banerjee, 2023). Furthermore, intensive agricultural practices associated with these crops often require substantial fertilizer inputs, which may contribute to soil degradation and land pollution. Overall, despite their high technological readiness and lower production costs, the broader sustainability of first-generation biofuels remains contested, as their environmental and socio-economic impacts depend heavily on land availability, agricultural management practices, and regional resource constraints (Banerjee, 2023).

5.2. *Second-generation biofuels (2 G)*

Second-generation biofuels were developed to address the drawbacks of first-generation pathways by exploiting lignocellulosic biomass (LCB) such as crop residues, forestry by-products, non-food energy crops, and animal manures (Pandiyan et al., 2019; Ali et al., 2024). Converting LCB into fuels requires multiple steps, with pre-treatment playing a central role in breaking the rigid structure of cellulose–hemicellulose–lignin complexes and thereby improving enzymatic hydrolysis and sugar recovery (Pandiyan et al., 2019; Kag et al., 2022). The type of pre-treatment selected, whether physical, chemical, or biological, must be chosen and optimized carefully to keep costs down, reduce the formation of inhibitory compounds, and improve the overall sustainability of the process (Kag et al., 2022). Among the thermochemical options, gasification converts LCB at high temperature and sub-stoichiometric oxygen levels to syngas, a mixture of CO and H_2, which can be used directly for power and heat or upgraded into liquid biofuels through Fischer–Tropsch synthesis (Gizaw et al., 2024; Banerjee, 2023). Pyrolysis, conducted at 300–700 °C in the absence of oxygen, generates bio-oil, biochar, and gases; the proportions depend on process temperature, and bio-oil can either be combusted as fuel or upgraded into higher-value products (Moura et al., 2022; Ufitikirezi et al., 2024; Quevedo-Amador et al., 2024). Torrefaction, a mild pyrolytic treatment, enhances the calorific value of biomass and produces biochar with coal-like properties. Its performance, however, can vary depending on whether it is carried out in wet, dry, or steam conditions, and scale-up still faces issues such as tar formation, pollutant emissions, and fluctuating ash quality (Banerjee, 2023).

Anaerobic digestion (AD) represents a mature biochemical option, where mixed microbial communities convert organic residues into biogas ($CH_4 + CO_2$). AD supports combined heat and power generation (Alengebawy et al., 2024; Forbes et al., 2016), and biogas upgrading yields biomethane suitable for grid injection (Roudneshin and Sosa, 2024). Digestate, the main by-product, is valuable as an organic fertilizer (Alengebawy et al., 2024). Process stability and methane yields can be enhanced through anaerobic co-digestion (AcoD) of complementary substrates and through pre-treatments that enhance biodegradability (Adnane et al., 2024).

Finally, hydrothermal processes use hot, pressurized water to depolymerize biomass. Hydrothermal liquefaction (HTL) produces bio-oil, while hydrothermal carbonization (HTC) yields hydrochar, a carbon-rich solid that can substitute fossil coal or serve as a precursor for value-added applications (Ufitikirezi et al., 2024; Kassim et al., 2022). Beyond these technological aspects, the sustainability and readiness level of 2 G pathways show a combination of strengths and limitations. These systems rely on abundant and underutilised agricultural and forestry residues that do not compete with food production, thereby reducing pressure on land and contributing to improved waste management (Pandiyan et al., 2019). The use of non-edible lignocellulosic biomass can lead to significant greenhouse gas reductions, typically in the range of 50–70 % depending on feedstock and process configuration. At the same time, the conversion of lignocellulosic biomass is still limited by the high cost and energy demand of pre-treatments, which makes industrial-scale implementation difficult (Banerjee, 2023). Regarding technological maturity, second-generation technologies have progressed beyond laboratory development but remain largely at a pilot-to-early-commercial stage, in which core processes have been demonstrated but require further optimisation and cost reductions to enable broad deployment (Pandiyan et al., 2019).

5.3. *Third-generation biofuels (3 G)*

Third-generation biofuels are primarily derived from algae and other aquatic microorganisms, which are increasingly studied as renewable feedstocks (Ali et al., 2024). Algae offer several advantages over terrestrial crops, including rapid growth rates, the capacity to thrive on non-arable land, and their ability to grow in diverse water systems such as freshwater, seawater, and even wastewater, while simultaneously contributing to CO_2 sequestration (Quevedo-Amador et al., 2024). Their photosynthetic efficiency is higher than that of land plants, allowing them to capture and store carbon more effectively. Estimates indicate that microalgae can fix CO_2 at rates 10–50 times greater than terrestrial plants (Vassilev et al., 2016). To improve energy recovery, algal biomass often requires pre-treatments, physical, chemical, or biological, with microbial consortia showing good potential for increasing biodegradability and conversion performance efficiency (Banerjee, 2023; Zabed et al., 2019).

Several technological pathways are available for converting algae into biofuels. Lipid-rich species can be processed through lipid extraction followed by transesterification to obtain biodiesel (Quevedo-Amador et al., 2024). Residual biomass, or whole algal cultures, may be subjected to anaerobic digestion for biogas production. Thermochemical pathways such as pyrolysis can also convert algae into bio-oil, which may subsequently undergo transesterification to produce biodiesel. Hydrolysed algal material can be fermented into bioethanol or other bio alcohols (Ali et al., 2024). Some microalgal species can also generate biohydrogen through photobiological processes (Garg et al., 2024; Adetunji et al., 2023), though yields depend heavily on light availability, nutrient supply (e.g., nitrogen, phosphorus, iron, silicon), and growth conditions. Cultivation strategies for microalgae include open raceway ponds, which are low-cost but susceptible to contamination and limited productivity due to evaporation and CO_2 scarcity; closed photobioreactors, which provide greater control over environmental variables and improve biomass quality; and heterotrophic cultivation, where algae grow without light by using organic carbon sources, producing biomass often richer in lipids. Growth in these systems depends on factors such as pH, salinity, and temperature (typically 15–30 °C), while continuous mixing is required at large scale to avoid sedimentation (Zhang et al., 2023). Despite these advantages, algae-based biofuels face significant barriers, mainly due to high production and processing costs, as well as the lack of mature technological infrastructure for large-scale deployment (Vassilev et al., 2016).

Another pathway sometimes included within third-generation approaches is dark fermentation. This anaerobic process uses facultative or obligate microorganisms (e.g., *Clostridium beijerinckii, Enterobacter cloacae, Escherichia coli*) to convert sugar-rich substrates into molecular hydrogen, organic acids, and alcohols. Since it operates without light and oxygen, dark fermentation can process a wide variety of organic wastes, does not require sterile conditions and is relatively low-cost. Hydrogen yields depend strongly on the choice of substrate and pre-treatment applied. The process can run under mesophilic or thermophilic conditions and produces valuable by-products such as volatile fatty acids, acetic acid, and butyric acid, which can be further valorised into advanced biofuels or other bioproducts (Ubando et al., 2022).

Third-generation pathways present several environmental advantages, primarily because microalgae do not compete with arable land and can be cultivated on marginal areas or integrated into wastewater treatment systems, contributing simultaneously to nutrient removal and CO_2 recycling. Their high photosynthetic efficiency and rapid biomass accumulation translate into potentially lower life-cycle greenhouse gas emissions compared with lignocellulosic and starch-based pathways (Vassilev et al., 2016; Quevedo-Amador et al., 2024). Despite this favourable environmental profile, the economic feasibility of 3 G biofuels remains limited. Lipid extraction, biomass harvesting, and downstream upgrading are capital- and energy-intensive steps, and several studies emphasise that these processes remain one of the major cost bottlenecks hindering commercialization (Zabed et al., 2019; Ali et al., 2024). Scalability is another challenge: although microalgae exhibit higher productivity than lignocellulosic feedstocks, industrial-scale systems require strict control of environmental variables (light, nutrient supply, CO_2 availability), and productivity fluctuations remain difficult to manage in open systems (Quevedo-Amador et al., 2024). As a result, the technological readiness level of most 3 G routes remains low, with many conversion technologies still confined to laboratory or pilot-scale development (Vassilev et al., 2016).

5.4. *Fourth-generation biofuels (4 G)*

Fourth-generation biofuels represent a further step toward advanced, highly sustainable, and efficient energy production systems (Ali et al., 2024). This generation primarily relies on synthetic biology and bioengineering approaches, where genetically modified microorganisms such as yeasts, cyanobacteria, and microalgae are tailored to convert carbon dioxide or biomass directly into fuels (Quevedo-Amador et al., 2024). Through genetic modifications, these microorganisms can be designed to produce improved enzymes, tolerate inhibitors present in biomass hydrolysates, or even secrete biofuels directly, thus simplifying recovery and reducing process costs (Pandiyan et al., 2019). The spectrum of products includes ethanol, butanol, biodiesel, hydrogen, methane, isoprene, gasoline, and even aviation fuels (Alalwan et al., 2019).

A set of emerging technologies supports the development of this generation. One key concept is solar biofuels, in which engineered microorganisms are employed in photocatalytic or bio electrochemical processes to transform solar energy, water, and CO_2 into liquid fuels such as ethanol or butanol (Ali et al., 2024; Awogbemi et al., 2022). Another promising field is Bio electrochemical Systems (BES), including microbial fuel cells (MFCs) and microbial electrolysis cells (MECs). These systems rely on electroactive microorganisms to convert organic matter directly into electricity or biohydrogen (Bhatia et al., 2018; ElMekawy et al., 2015; Ramanaiah et al., 2023). For example, MFCs are able to generate electricity while simultaneously treating wastewater (Ramanaiah et al., 2023).

When dealing with complex substrates such as food waste, pre-treatment becomes a critical step for enhancing MFC efficiency. As discussed by Dilip Kumar et al., 2022, pre-treatments help break down complex polymers, solubilize organic matter, and make more biodegradable compounds available to electroactive microorganisms., thereby improving electron recovery and ensuring more stable operation. Various approaches can be employed depending on the type of feedstock, including thermal, mechanical, chemical, or enzymatic pre-treatments. The integration of MFCs with processes such as anaerobic digestion or fermentation can increase energy recovery and treatment efficiency (ElMekawy et al., 2015).

Despite these advances, BES technologies still face important challenges. According to Ramya et al. (2022), the main barriers include the high costs of operation, difficulties in scaling up from laboratory to industrial applications, and the relatively low electrical output compared with conventional systems. From a sustainability and deployment perspective, fourth-generation biofuels are still at a very early stage of development. Current research efforts focus on genetically modified algal strains with enhanced lipid content, faster growth, improved tolerance to harsh conditions and higher CO_2 sequestration capacity, in order to maximise biomass productivity and carbon capture. However, Banerjee, 2023 reports that these processes are still being researched and that the environmental impacts of such genetic modifications in micro- and macroalgae remain largely unknown, raising relevant questions about their long-term ecological safety. In addition, the cost of processing and production is expected to be high, so that the economic feasibility of these routes is not yet demonstrated. Taken together, these aspects indicate that, although fourth-generation biofuels are conceptually promising, they currently exhibit low technological maturity and are far from large-scale commercial deployment.

5.5. *Integration of technologies and biorefinery*

A promising strategy to fully exploit biomass resources while reducing waste is the biorefinery concept, which integrates multiple conversion routes to obtain a wide spectrum of outputs, such as biofuels, bio-based chemicals, and energy carriers (Banerjee, 2023). Compared with single conversion technologies (SCT), combining multiple processes (ICT) can help overcome the limits of individual methods. For example, coupling anaerobic digestion with pyrolysis has been shown to enhance electricity generation by up to 42 % compared to anaerobic digestion alone (Kassim, Thomas, and Afolabi, 2022). These integrated biorefinery systems not only improve total energy recovery but also allow better use of by-products, in line with circular economy principles (Kag et al., 2022).

The following table (Table 1) provides a summary of the four generations of sustainable bioenergy technologies, outlining the types of biomasses employed, associated pre-treatment strategies, and main technological features.

To complement this structural overview, a second summary table (Table 2) has been included to provide a comparative assessment of the four biofuel generations. While Table 1 focuses on the types of biomasses, pre-treatment strategies and key technological features

Table 1
Overview of the four technological generations for the sustainable recovery of bioenergy. For each generation, the reference biomasses, main pre-treatments, associated sustainable technologies, and distinctive key point are reported.

Generation	Type of biomass	Pre-treatment	Technology	Biofuel	Pros	Cons	Reference
First	Sugar-rich food crops (Sugarcane, sugar beet, cereals, and tuber)	Enzymatic hydrolysis	Alcoholic fermentation	Bioethanol	- Consolidated and easily scalable process.	- Problems with food security, land use, and environmental impact. - Fewer development opportunities compared to other generations.	(Ali et al. 2024; Banerjee, 2023; Kag et al. 2022; Quevedo-Amador et al. 2024; Santhakumari et al. 2024)
	Vegetable oils (soybean, rapeseed, sunflower, and palm) and animal fats	Acid pre-treatment	Transesterification	Biodiesel e glycerol			
Second	Lignocellulosic (cereal straw, corn stover, sugarcane, forestry by-products, non-food energy crops, municipal solid waste) Algae, Animal manure	Milling and grinding, microwave irradiation, ultrasonication, steam explosion, liquid hot water, acid pre-treatment, organosoly, ionic liquid, ozonolysis, AFEX, fungal, enzymatic, Mcons, Ensiling,SF	Gasification Pyrolysis, Torrefaction Anaerobic digestion Hydrothermal processing	Syngas Biochar, bio-oil, biogas Biochar, coke Biogas Hydrochar	- Non-food biomass, better prospects compared to the first generation.	- Biomass recalcitrant to degradation. - Pre-treatments required, which can be costly both economically and energetically, and may create inhibitors.	(Adnane et al. 2024; Alengebawy et al. 2024; Ali et al. 2024; Banerjee, 2023; ElMekawy et al. 2015; Kag et al. 2022; Kang et al. 2022; Kassim et al., 2022; Moura et al. 2022; Pandiyan et al. 2019; Ufitikirezi et al. 2024; Zabed et al. 2019)
Third	Algae	Microwave irradiation, ultrasonication, torrefaction, hydrothermal carbonization, acid pre-treatment, enzymatic hydrolysis	Transesterification Anaerobic digestion, Pyrolysis Fermentation Biohydrogen production	Biodiesel Biogas Biodiesel Bioethanol Biohydrogen	- High growth rate, in non-agricultural land and in freshwater, saline, or wastewater. - CO2 sequestration during growth, using sunlight to synthesize biomass. - Higher energy yield with biological pre-treatments compared to lignocellulosic biomass.	- Pre-treatments can be complex and costly - Still in development.	(Adnane et al. 2024; Ali et al. 2024; Banerjee, 2023; Garg et al. 2024; Kag et al. 2022; Kang et al. 2022; Quevedo-Amador et al. 2024; Santhakumari et al. 2024; Zabed et al. 2019)
Fourth	Microalgae, cyanobacteria, yeasts, wastewater, agricultural waste and animal manure	Genetic engineering and microwave irradiation, ultrasonication, torrefaction, hydrothermal carbonization, acid pre-treatment, drying	Solar fuels	Ethanol, butanol	- Improved CO2 sequestration and bio-oil production through genetic engineering.	- Requires complex and costly pre-treatment. - Still in development.	(Ali et al. 2024; Awogbemi e Kallon, 2022; Banerjee, 2023; Bhatia et al., 2018; Dilip Kumar et al. 2022; ElMekawy et al. 2015; Garg et al. 2024; Ramanaiah et al. 2023; Quevedo-Amador et al. 2024)
	Electroactive microorganisms, wastewater, agricultural waste and animal manure		Bio electrochemical systems	Bioelectricity, biohydrogen	- Potential integration with wastewater treatment.		

Table 2

Comparative assessment of first-, second-, third- and fourth-generation biofuels across key sustainability metrics.

Generation	Environmental Performance	Economic Feasibility	Scalability	Technological Maturity
1st generation	Moderate GHG reductions; significant land, water and food-security pressures	Low production costs; established markets	High – fully commercialised	High TRL
2nd generation	Reduced GHG emissions; no food competition; valorisation of residues	Limited by costly and energy-intensive pre-treatments	Moderate – process complexity limits expansion	Medium TRL (pilot–early commercial)
3rd generation	High CO_2 fixation; land-independent cultivation; promising environmental profile	High OPEX due to harvesting, dewatering and downstream processing	Low – sensitive to environmental variability	Low TRL (lab–pilot)
4th generation	Potential for enhanced CO_2 utilisation; environmental impacts of GM strains still uncertain	High production costs; economic viability not yet demonstrated	Very low – biosafety and regulatory hurdles	Very low TRL (research stage)

associated with each generation, Table 2 evaluates these pathways in terms of their environmental performance, economic feasibility, scalability and technological maturity. Presenting the tables consecutively offers a clearer and more coherent synthesis of the technological landscape and its sustainability implications.

6. Discussions and future perspectives

The evaluation of different biomass feedstocks for bioenergy production makes it clear that a comprehensive approach, that balances environmental, economic, and social considerations, is necessary,. Sugar- and starch-rich materials are attractive because they can be converted through simple and well-known processes, but relying on food crops may create competition with food markets and put additional pressure on agricultural systems. Lignocellulosic feedstocks, on the other hand, are abundant and versatile but demand costly and energy-intensive pre-treatment steps. Organic wastes are particularly important since they simultaneously address waste management issues while serving as substrates for biogas production. Algae are also becoming an interesting option thanks to their high lipid content for biodiesel production and their lack of competition with arable land, although large-scale use is still limited by high production costs and significant resource needs. Choosing the most suitable pre-treatment method depends on the characteristics of the feedstock, the conversion route, economic constraints, and environmental criteria. When different feedstocks and technologies are compared, the need for integrated approaches becomes clear, as these can improve yields while reducing environmental and social drawbacks. The progression from one generation of biofuels to the next illustrates efforts to overcome the limitations of earlier approaches. First-generation fuels benefit from simple conversion processes and relatively low costs, but they are associated with concerns such as food insecurity, land-use change, water stress, and deforestation. Second-generation fuels, based on residues and non-food crops, help mitigate these concerns and can lower greenhouse gas emissions and pollution, but they still require complex processing steps and often deliver lower energy yields. Third-generation biofuels, largely based on algae, offer advantages such as high photosynthetic efficiency, capacity for CO_2 fixation, and significant lipid productivity. However, cultivation, harvesting, and processing are resource-intensive and economically challenging. Fourth-generation fuels seek to overcome these limitations by harnessing synthetic biology and genetic engineering to modify microalgae and microorganisms, enhancing CO_2 sequestration, stress resistance, and biofuel productivity. Despite their potential, these advanced approaches remain at the research stage and face hurdles regarding biosafety, economic viability, and regulatory acceptance.

A comparison across the four biofuel generations shows that they differ not only in terms of feedstocks and conversion performance, but also in the types of sustainability challenges they present. First-generation biofuels exhibit the highest technological readiness yet pose significant socio-environmental risks; second-generation pathways achieve better alignment with circularity principles but still struggle with costly pre-treatments and limited scalability; third-generation systems offer important environmental gains but are hampered by high energy demand and operational complexity; and fourth-generation pathways, while conceptually the most advanced in terms of carbon utilisation and strain optimisation, remain confined to laboratory-scale research and face unresolved economic and biosafety issues. Taken together, this comparison shows that none of the generations can be considered universally preferable. Instead, the potential of each technology depends on regional biomass availability, infrastructure readiness, and long-term sustainability priorities, reinforcing the need for integrated, context-specific strategies rather than a linear "next-generation" progression.

Despite the breadth of evidence reviewed, several limitations should be acknowledged to contextualize the findings and guide future research priorities. The current literature shows a clear geographical bias, with a predominance of studies conducted in specific regions where biomass availability, agricultural practices, and waste management infrastructures differ significantly. This uneven distribution may restrict the generalisability of some technological conclusions. Furthermore, the heterogeneity of the technologies investigated, ranging from biochemical and thermochemical to photobiological, and bio electrochemical pathways, complicates direct comparisons and highlights the need for harmonised evaluation frameworks. Finally, although many studies report yields, efficiencies, or process performance indicators, comprehensive life-cycle assessments remain scarce across almost all technological categories. The absence of systematic LCA evidence limits the ability to quantify environmental trade-offs and prevents a robust evaluation of the long-term sustainability of emerging bioenergy systems.

7. Conclusions

Biomass represents a diverse and versatile feedstock with significant potential for advancing sustainable bioenergy. Selecting the right appropriate conversion pathway requires evaluating a range of interrelated factors, such as local resource availability, the physico-chemical characteristics of the material, economic aspects tied to production and logistics, and wider environmental and socio-economic impacts. Bioenergy technologies can contribute not only to economic growth, through cost savings and the valorisation of waste into marketable products—but also to social progress by creating employment, supporting rural livelihoods, and improving both energy access and quality of life. At the same time, they play a critical role in tackling global challenges, including the growing demand for energy, the need for effective waste management, and the pursuit of energy security with reduced environmental pollution.

To unlock this potential, it is crucial to design pre-treatment and conversion processes that are cost-effective, energy-efficient, and environmentally sustainable. Moving toward a circular bioeconomy will require coordinated action across different stakeholders, including governments, research institutions, industry actors, and regulatory bodies. Only through integrated strategies and the efficient valorisation of the many types of biomasses available can the transition to a secure, resilient, and sustainable energy future be fully achieved

CRediT authorship contribution statement

Francesca Valenti: Writing – review & editing, Visualization, Supervision, Resources, Conceptualization. **Mirko Maraldi:** Writing – review & editing, Validation, Methodology, Formal analysis. **Emanuele Spizzirri:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation.

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Data availability

Data will be made available on request.

References

Adetunji, Adegoke Isiaka, Oberholster, Paul Johan, e, Erasmus, Mariana, 2023. From Garbage to Treasure: A Review on Biorefinery of Organic Solid Wastes into Valuable Biobased Products. Bioresour. Technol. Rep. 24 (dicembre), 101610. https://doi.org/10.1016/j.biteb.2023.101610.

Adnane, Imane, Taoumi, Hamza, Elouahabi, Karim, Lahrech, Khadija, Oulmekki, Abdellah, 2024. Valorization of Crop Residues and Animal Wastes: Anaerobic Co-Digestion Technology. Heliyon 10 (5), e26440. https://doi.org/10.1016/j.heliyon.2024.e26440.

Alakangas, Eija, 2016. Biomass and Agricultural Residues for Energy Generation. In Fuel Flexible Energy Generation. Elsevier, pp. 59–96. https://doi.org/10.1016/B978-1-78242-378-2.00003-1.

Alalwan, Hayder A., Alminshid, Alaa H., e, Aljaafari, Haydar A.S., 2019. Promising Evolution of Biofuel Generations. Subject Review. Renew. Energy Focus 28 (marzo), 127–139. https://doi.org/10.1016/j.ref.2018.12.006.

Alengebawy, Ahmed, Ran, Yi, Osman, Ahmed I., Jin, Keda, Samer, Mohamed, Ai, Ping, 2024. Anaerobic Digestion of Agricultural Waste for Biogas Production and Sustainable Bioenergy Recovery: A Review. Environ. Chem. Lett. 22 (6), 2641–2668. https://doi.org/10.1007/s10311-024-01789-1.

Ali, Shehbaz, Rani, Abida, Sethupathy, Sivasamy, Liaqat, Fakhra, Shunkai, Wang, Shah, Tawaf Ali, Zhu, Daochen, 2024. Advanced Technologies for Transforming Biomass to Biofuels (Studies in Systems, Decision and Control). In: Mabrouki, Jamal, Azrour, Mourade (Eds.), Integrated Solutions for Smart and Sustainable Environmental Conservation, 527. Springer Nature Switzerland, Cham, pp. 47–64. https://doi.org/10.1007/978-3-031-55787-3_4.

Aravind Kumar, J., Sathish, S., Krithiga, T., et al., 2022. A Comprehensive Review on Bio-Hydrogen Production from Brewery Industrial Wastewater and Its Treatment Methodologies. Fuel 319 (July), 123594. https://doi.org/10.1016/j.fuel.2022.123594.

Awogbemi, Omojola, Von Kallon, e Daramy Vandi, 2022. Valorization of Agricultural Wastes for Biofuel Applications. Heliyon 8 (10), e11117. https://doi.org/10.1016/j.heliyon.2022.e11117.

Banerjee, Nilanjana, 2023. Biomass to Energy — an Analysis of Current Technologies, Prospects, and Challenges. BioEnergy Res. 16 (2), 683–716. https://doi.org/10.1007/s12155-022-10500-7.

Bhatia, Shashi Kant, Joo, Hwang-Soo, Yang, Yung-Hun, 2018. Biowaste-to-Bioenergy Using Biological Methods – A Mini-Review. Energy Convers. Manag. 177 (December), 640–660. https://doi.org/10.1016/j.enconman.2018.09.090.

Dilip Kumar, Shanmugam, Yasasve, Madhavan, Karthigadevi, Guruviah, Aashabharathi, Manimaran, Subbaiya, Ramasamy, Karmegam, Natchimuthu, e, Govarthanan, Muthusamy, 2022. Efficiency of Microbial Fuel Cells in the Treatment and Energy Recovery from Food Wastes: Trends and Applications - A Review. Chemosphere 287 (gennaio), 132439. https://doi.org/10.1016/j.chemosphere.2021.132439.

ElMekawy, Ahmed, Srikanth, Sandipam, Bajracharya, Suman, Hegab, Hanaa M., Singh Nigam, Poonam, Singh, Anoop, Mohan, S.Venkata, Pant, Deepak, 2015. Food and Agricultural Wastes as Substrates for Bioelectrochemical System (BES): The Synchronized Recovery of Sustainable Energy and Waste Treatment. Food Res. Int. 73 (July), 213–225. https://doi.org/10.1016/j.foodres.2014.11.045.

Fagundes, Victória Dutra, Freitag, João Felipe, Simon, Viviane, Colla, Luciane Maria, 2024. Enzymatic Hydrolysis of Food Waste for Bioethanol Production. Rev. Bras. De. Ciências Ambient. 59 (June), e1978. https://doi.org/10.5327/Z2176-94781978.

Forbes, E.G.A., Olave, R.J., Johnston, C.R., Browne, J.D., Relf, J., 2016. Biomass and Bio-Energy Utilisation in a Farm-Based Combined Heat and Power Facility. Biomass.. Bioenergy 89 (June), 172–183. https://doi.org/10.1016/j.biombioe.2016.03.005.

Garg, Anushka, Basu, Soumen, Shetti, Nagaraj P., Bhattu, Monika, Alodhayb, Abdullah N., Pandiaraj, Saravanan, 2024. Biowaste to Bioenergy Nexus: Fostering Sustainability and Circular Economy. Environ. Res. 250 (June), 118503. https://doi.org/10.1016/j.envres.2024.118503.

Gizaw, Getachew, Desta, Periyasamy, Selvakumar, Tassew Redda, Zinnabu, Baskar, Gurunathan, 2024. Industrial Organic Waste and Byproducts as Sustainable Feedstock for Bioenergy Production (Energy, Environment, and Sustainability). In: Baskar, Gurunathan, Ashokkumar, Veeramuthu, Rokhum, Samuel Lalthazuala, Moholkar, Vijayanand Suryakant (Eds.), Circular Bioeconomy Perspectives in Sustainable Bioenergy Production. Springer Nature Singapore, Singapore, pp. 91–116. https://doi.org/10.1007/978-981-97-2523-6_4.

Kag, Sonika, Kukreti, Neha, Ruhal, Rohit, Mann, Sweeti, Sharma, Jaigopal, Kataria, Rashmi, 2022. Recent Technologies for Lignocellulose Biomass Conversion to Bioenergy and Biochemicals (Energy, Environment, and Sustainability). In: Kadapakkam Nandabalan, Yogalakshmi, Garg, Vinod Kumar, Labhsetwar, Nitin K., Singh, Anita (Eds.), Zero Waste Biorefinery. Springer Nature Singapore, Singapore, pp. 23–56. https://doi.org/10.1007/978-981-16-8682-5_2.

Kang, Xihui, Xu, Chao, Lin, Richen, Song, Bing, Wall, David, Murphy, Jerry D., 2022. Feedstock Pretreatment for Enhanced Anaerobic Digestion of Lignocellulosic Residues for Bioenergy Production. In Biomass, Biofuels, Biochemicals. Elsevier, pp. 253–282. https://doi.org/10.1016/B978-0-323-90633-3.00004-3.

Kassim, Falilat O., Thomas, C.L.Paul, Afolabi, Oluwasola O.D., 2022. Integrated Conversion Technologies for Sustainable Agri-Food Waste Valorization: A Critical Review. Biomass.. Bioenergy 156 (January), 106314. https://doi.org/10.1016/j.biombioe.2021.106314.

Kumar, J.Aravind, Sathish, S., Prabu, D., et al., 2023. Agricultural Waste Biomass for Sustainable Bioenergy Production: Feedstock, Characterization and Pre-Treatment Methodologies. Chemosphere 331 (August), 138680. https://doi.org/10.1016/j.chemosphere.2023.138680.

kumari, Santha, Bai, Meera, Pandi, Ezhilarasi, Mohan, Manjima, Reji Daniel, Aparna, Balakrishnan, Vanavil, 2024. Biomass: Resources and Sustainable Utilization (edited by). In: Garg, Vinod Kumar, Kataria, Navish (Eds.), Bioeconomy for Sustainability. Springer Nature Singapore, Singapore, pp. 3–39. https://doi.org/10.1007/978-981-97-1837-5_1 (edited by).

Moher, David, Alessandro Liberati, Jennifer Tetzlaff, and Douglas G.Altman. 2015. “Linee guida per il reporting di revisioni sistematiche e meta-analisi: il PRISMA Statement.”

Moura, Patrícia, Henriques, João, Alexandre, Jorge, Oliveira, Ana Cristina, Abreu, Mariana, Gírio, Francisco, Catarino, Justina, 2022. Sustainable Value Methodology to Compare the Performance of Conversion Technologies for the Production of Electricity and Heat, Energy Vectors and Biofuels from Waste Biomass. Clean. Waste Syst. 3 (December), 100029. https://doi.org/10.1016/j.clwas.2022.100029.

Negi, Sushant, Jaswal, Gaurav, Dass, Kali, Mazumder, Koushik, Elumalai, Sasikumar, Roy, e Joy K., 2020. Torrefaction: A Sustainable Method for Transforming of Agri-Wastes to High Energy Density Solids (Biocoal). Rev. Environ. Sci. Bio/Technol. 19 (2), 463–488. https://doi.org/10.1007/s11157-020-09532-2.

Nguyen, Luong N., Kumar, Jeevan, Vu, Minh T., et al., 2021. Biomethane Production from Anaerobic Co-Digestion at Wastewater Treatment Plants: A Critical Review on Development and Innovations in Biogas Upgrading Techniques. Sci. Total Environ. 765 (April), 142753. https://doi.org/10.1016/j.scitotenv.2020.142753.

Niyogi, Arindam, Sarkar, Priyanka, Bhattacharyya, Soumyadeb, Pal, Souvik, Mukherjee, Subhankar, 2024. Harnessing the Potential of Agriculture Biomass: Reuse, Transformation and Applications in Energy and Environment (July). Environ. Sci. Pollut. Res.. https://doi.org/10.1007/s11356-024-34232-7.

Pallath, Nisha, Sajeena, Tharakupeedikayil Abdul Majeed, Chemparathy, Shiji M., Varghese, Shalet, 2024. Biomass: Conversion, Utilization, and Environmental Impact (Materials Horizons: From Nature to Nanomaterials). In: Thomas, Sabu, Chirayil, Cintil Jose, Varghese, Rini Thresia (Eds.), Handbook of Advanced Biomass Materials for Environmental Remediation. Springer Nature Singapore, Singapore, pp. 13–29. https://doi.org/10.1007/978-981-97-4300-1_2.

Pandiyan, K., Singh, Arjun, Singh, Surender, Saxena, Anil Kumar, Nain, Lata, 2019. Technological Interventions for Utilization of Crop Residues and Weedy Biomass for Second Generation Bio-Ethanol Production. Renew. Energy 132 (March), 723–741. https://doi.org/10.1016/j.renene.2018.08.049.

Quevedo-Amador, Ricardo A., Escalera-Velasco, Blanca Paloma, Arias, Aida M.Ramírez, Reynel-Ávila, Hilda E., Moreno-Piraján, Juan C., Giraldo, Liliana, Bonilla-Petriciolet, A., 2024. Application of Waste Biomass for the Production of Biofuels and Catalysts: A Review. Clean. Technol. Environ. Policy 26 (4), 943–997. https://doi.org/10.1007/s10098-023-02728-4.

Ramanaiah, S.V., Chandrasekhar, K., Cordas, Cristina M., Potoroko, Irina, 2023. Bioelectrochemical Systems (BESs) for Agro-Food Waste and Wastewater Treatment, and Sustainable Bioenergy-A Review. Environ. Pollut. 325 (May), 121432. https://doi.org/10.1016/j.envpol.2023.121432.

Ramya, M., e, Senthil Kumar, P., 2022. A Review on Recent Advancements in Bioenergy Production Using Microbial Fuel Cells. Chemosphere 288 (febbraio), 132512. https://doi.org/10.1016/j.chemosphere.2021.132512.

Roudneshin, Maryam, Sosa, Amanda, 2024. Optimising Agricultural Waste Supply Chains for Sustainable Bioenergy Production: A Comprehensive Literature Review. Energies 17 (11), 2542. https://doi.org/10.3390/en17112542.

Sagar, Narashans Alok, Pathak, Meenakshi, Sati, Hansika, Agarwal, Surbhi, e, Pareek, Sunil, 2024. Advances in Pretreatment Methods for the Upcycling of Food Waste: A Sustainable Approach. Trends Food Sci. Technol. 147 (maggio), 104413. https://doi.org/10.1016/j.tifs.2024.104413.

Sharma, Chhavi, Pathak, Puneet, Gautam, Sneh, 2023. Transforming Agri-Crop Residue Biomass for Value Addition: An Innovative Strategy Toward Resilient Circular Economy (edited by). In: Thomas, Sabu, Hosur, Mahesh, Pasquini, Daniel, Chirayil, Cintil Jose (Eds.), Handbook of Biomass. Springer Nature Singapore, Singapore, pp. 1–26. https://doi.org/10.1007/978-981-19-6772-6_66-1 (edited by).

Sharma, Rama, 2024. Agro-Industrial Waste to Energy - Sustainable Management. Sustain. Mater. Technol. 41 (September), e01117. https://doi.org/10.1016/j.susmat.2024.e01117.

Ubando, Aristotle T., Chen, Wei-Hsin, Hurt, Dennis A., Conversion, Ariel, Rajendran, Saravanan, e, Lin, Sheng-Lun, 2022. Biohydrogen in a Circular Bioeconomy: A Critical Review. Bioresour. Technol. 366 (dicembre), 128168. https://doi.org/10.1016/j.biortech.2022.128168.

Ufitikirezi, Jean De. Dieu Marcel, Filip, Martin, Ghorbani, Mohammad, Zoubek, Tomáš., Olšan, Pavel, Bumbálek, Roman, Strob, Miroslav, et al., 2024. Agricultural Waste Valorization: Exploring Environmentally Friendly Approaches to Bioenergy Conversion. Sustainability 16 (9), 3617. https://doi.org/10.3390/su16093617.

Vassilev, Stanislav V., e, Vassileva, Christina G., 2016. Composition, Properties and Challenges of Algae Biomass for Biofuel Application: An Overview. Fuel 181 (ottobre), 1–33. https://doi.org/10.1016/j.fuel.2016.04.106.

Zabed, Hossain M., Akter, Suely, Yun, Junhua, Zhang, Guoyan, Awad, Faisal N., Qi, Xianghui, e, Sahu, J.N., 2019. Recent Advances in Biological Pretreatment of Microalgae and Lignocellulosic Biomass for Biofuel Production. Renew. Sustain. Energy Rev. 105 (maggio), 105–128. https://doi.org/10.1016/j.rser.2019.01.048.

Zhang, G., Liu, J., Pan, X., Abed, A.M., Le, B.N., Ali, H.E., Ge, e Y., 2023. Latest avenues and approaches for biohydrogen generation from algal towards sustainable energy optimization: Recent innovations, artificial intelligence, challenges, and future perspectives, 20988–3 Int. J. Hydrog. Energy 48 (55). https://doi.org/10.1016/j.ijhydene.2022.10.224.