VALORIZATION OF AGRICULTURAL WASTE FOR SUSTAINABLE BIOFUEL PRODUCTION - A REVIEW
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VALORIFICAREA DEȘEURILOR AGRICOLE PENTRU PRODUCEREA SUSTENABILĂ DE BIOCOMBUSTIBILI – O SINTEZĂ

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DOI: https://doi.org/10.35633/inmateh-77-104

Keywords: *agricultural waste, biofuels, circular economy, waste management, sustainable agriculture, bibliometric analysis*

ABSTRACT
Population growth and technological progress significantly contribute to the climate change intensification, the increasing global energy demand, and the depletion of natural resources, while also generating massive amounts of waste. Agriculture is one of the main sectors with the highest biomass production, representing an essential factor for the bioeconomy. Agricultural wastes represent a sustainable and abundant source of organic matter, used in the production of biofuels, which are considered a promising alternative to meeting the global energy demand. Thus, considering the challenges associated with agricultural waste generation and their environmental impacts, this review aims to provide a comprehensive analysis of recent advances in the valorization of agricultural waste for sustainable biofuel production. The paper focuses on the main categories of agricultural waste, the associated conversion technologies, and the integration of these processes within the circular economy framework. In addition, to achieve the objectives of the study, a bibliometric analysis was conducted on publications from 2012–2024 indexed in the Web of Science Core Collection (WoS), highlighting research trends, leading journals, and thematic clusters in the field of agricultural waste valorization.

REZUMAT
Creșterea populației și progresul tehnologic contribuie semnificativ la amplificarea schimbărilor climatice, la creșterea cererii globale de energie și la epuizarea resurselor naturale, generând, totodată, cantități masive de deșeuri. Agricultura reprezintă unul dintre principalele sectoare cu cea mai mare producție de biomasă, constituind un factor esențial pentru bioeconomie. Deșeurile agricole reprezintă o sursă durabilă și abundentă de materie organică, utilizată în producția de biocombustibili, considerați o alternativă promițătoare pentru satisfacerea cererii globale de energie. Astfel, având în vedere provocările asociate cu generarea deșeurilor agricole și impactul acestora asupra mediului, această recenzie își propune să ofere o analiză cuprinzătoare a progreselor recente în valorificarea deșeurilor agricole pentru producția de biocombustibili sustenabili. Lucrarea se concentrează asupra principalelor categorii de deșeuri agricole, a tehnologiilor de conversie asociate și a integrării acestor procese în cadrul economiei circulare. În plus, pentru atingerea obiectivului lucrării, a fost realizată o analiză bibliometrică a publicațiilor din perioada 2012–2024, indexate în baza de date Web of Science Core Collection (WoS), care evidențiază tendințele de cercetare, principalele reviste și clusterele tematice din domeniul valorificării deșeurilor agricole.

INTRODUCTION
Population growth and technological progress significantly contribute to the climate change intensification, the increasing global energy demand, and the depletion of natural resources, while also generating massive amounts of waste *(Alan and Koker, 2023)*. Globally, fossil fuels are still the main source of energy, but the depletion of reserves is a major problem for the future and poses considerable economic challenges *(Boro et al., 2022)*. Furthermore, the use of fossil fuels has led to significant pollution of water and air resources, with the energy sector continuing to be the largest generator of carbon dioxide (CO_2) emissions *(Awogbemi and Kallon, 2022; Baz et al., 2021)*. An effective solution to overcome these challenges and meet energy demands is to use naturally available renewable materials *(Kour et al., 2019; Sharma et al., 2024).*

In addition, addressing these issues has created opportunities for the development of a circular economy based on innovative and sustainable technologies focused, among other things, on waste recycling and recovery *(Alan and Koker, 2023; Sikiru et al., 2024)*. Statistics show that globally, more than two billion tons of municipal solid waste are produced annually, and this increase contributes significantly to the environment degradation *(Statista, 2025).*

According to the World Bank's report *(Kaza et al., 2018),* global waste will increase by 70% from current levels until 2050, and greenhouse gas emissions from solid waste are estimated to rise to 2.6 billion tons of CO_2 equivalent per year if urgent action is not taken. Currently, one of the most urgent global challenges is the reduction and efficient management of waste *(Giacomello et al., 2025).*

Figure 1 shows the global waste generation per capita in 2016 and the outlook for the period 2030-2050 *(Kaza et al., 2018)*.

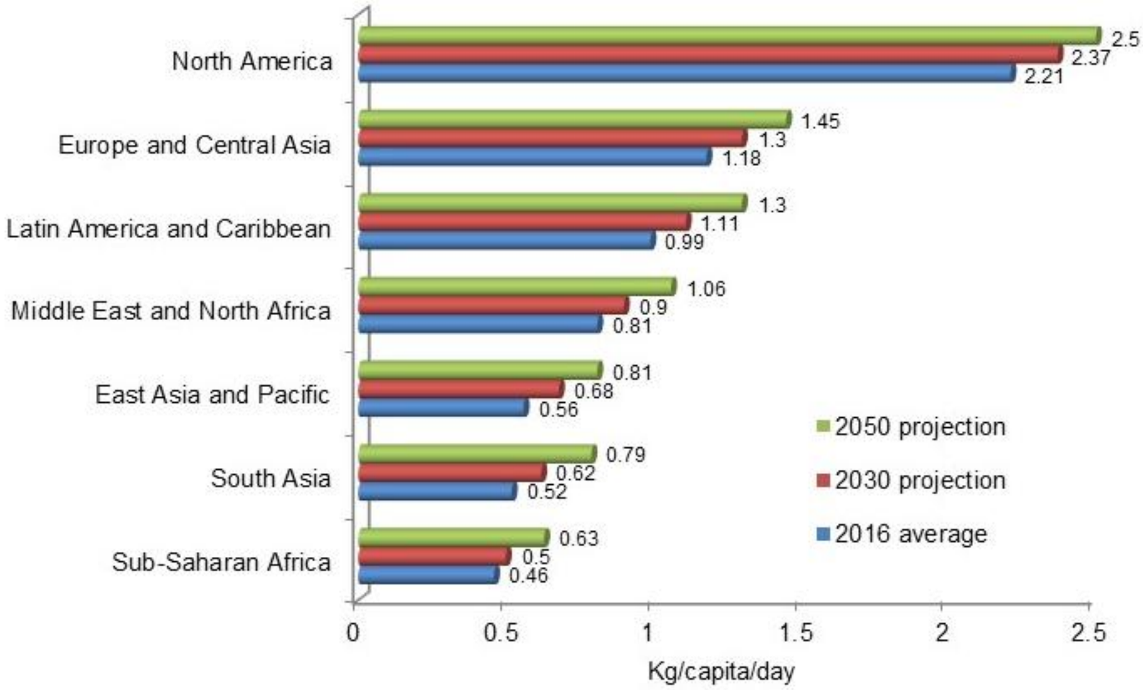

Fig. 1 - Global waste generation per capita in 2016 and projections for 2030-2050 *(Kaza et al., 2018)*

In recent decades, agriculture has become one of the most important economic sectors for many countries. Over the past 50 years, agricultural production has increased more than threefold, mainly caused by population growth *(FAO and OECD, 2019)*. Moreover, agriculture is one of the main sectors with the highest biomass production, constituting an essential factor for the bioeconomy *(Duque-Acevedo et al., 2020).* Globally, the amount of agricultural waste generated annually is estimated at around 998 million tons *(Parlato et al., 2022; Xiong et al., 2024).* Numerous studies show that agricultural waste is often disposed of by burning or landfilling, which poses a major global challenge from an environmental, economic, and social perspective *(Arora et al., 2023; Awogbemi and Kallon, 2022; Kaushal and Prashar, 2020; Lackner and Besharati, 2025; Raza et al., 2022)*. The storage of large amounts of agricultural waste on soil, associated with the accumulation of toxic compounds, pesticides, heavy metals, and pathogens, can lead to soil pollution, negatively affecting the health of plants, animals, and humans (*Bhatia and Sindhu, 2024*).

Therefore, given the negative effects of uncontrolled burning and storage of agricultural waste, it is necessary to adopt sustainable management practices aimed at protecting the environment and human health *(Raza et al., 2022)*. All these objectives must be achieved by minimizing the use of conventional energy sources, reducing pollutant emissions, and implementing a system based on the principle of "zero solid waste" *(Duque-Acevedo et al., 2020)*.

Agricultural waste management and the concept of circular economy are interconnected, in terms of promoting sustainable development within the agricultural sector. Furthermore, implementing the circular economy principles in agricultural waste recovery practices brings benefits such as reducing environmental pollution, increasing resource efficiency, and enhancing sustainability in the agricultural sector (*Dincă et al., 2024; Nattassha et al., 2020; Ufitikirezi et al., 2024)*.

The circular economy represents an economic model in which the waste produced by one process is not eliminated but reused as raw material for other technological processes. Thus, this model supports the transition from the current linear economy, based on the "take-make-use-dispose" principle, to a circular one by preventing and minimizing waste generation *(Edirisinghe et al., 2024; European Parliament, 2023; Nattassha et al., 2020)*. The principles of the circular economy are frequently applied in the agri-food sectors, where generated wastes are recovered in the form of energy, organic fertilizers, and other value-added products. In addition, the circular economy approach in agriculture is reflected in a sustainable and resilient food system, while also supporting the principles of sustainable development *(McCarthy et al., 2019; Nattassha et al., 2020).* Thus, sustainable waste management is an essential factor in the transition to a circular economy *(Nowakowski and Mrówczyńska, 2018).*

Figure 2 shows the main environmental risks associated with the burning and uncontrolled storage of agricultural waste.

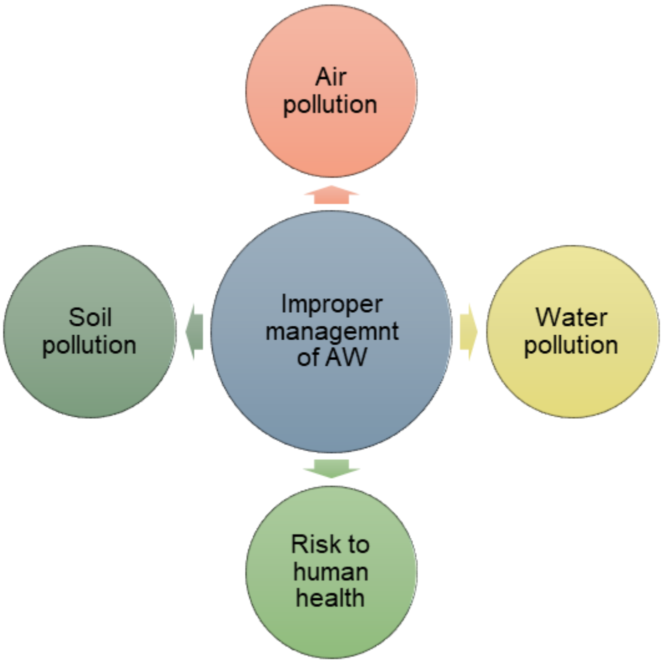

Fig. 2 - Environmental impact of uncontrolled burning and disposal of agricultural waste (AW)
(Jakhar et al., 2023; Chikezie Ogbu and Nnaemeka Okey, 2023)

Thus, considering the challenges associated with agricultural waste generation and their environmental impacts, this review aims to provide a comprehensive analysis of recent advances in the valorization of agricultural waste for sustainable biofuel production. The paper focuses on the main categories of agricultural waste, the associated conversion technologies, and the integration of these processes within the circular economy framework. To achieve this, a bibliometric analysis was conducted on publications from 2012–2024 indexed in the Web of Science Core Collection (WoS) database.

Agricultural waste represents a sustainable and abundant source of organic matter used in the production of biofuels, which are considered a promising alternative for meeting global energy demand *(Kour et al., 2019; Sikiru et al., 2024).* Agricultural waste can be converted into renewable energy sources such as biogas, biodiesel, bioethanol, biohydrogen, etc. using biochemical and thermochemical methods *(Guo et al., 2024).* Another sustainable approach to agricultural waste management is composting, which transforms organic residues into a stable, nutrient-rich product that can improve soil fertility. Thus, composting supports soil health and contributes to reducing greenhouse gas emissions *(Cismaru et al., 2025).* Another strategy for the valorization of agricultural waste, which supports the principles of the circular bioeconomy, involves the development of composite materials based on sludge matrices, where agricultural residues are used as filler materials *(Farcaș-Flamaropol et al., 2023)*. In addition, proper management of agricultural waste and its conversion into new raw materials reduces pollution and production costs, supporting the principles of the circular economy *(Parlato et al., 2022)*.

In summary, the study emphasizes that the efficient recovery of agricultural waste, through the production of biofuels and value-added products, can contribute to mitigating the effects of climate change and promoting sustainable agriculture.

AGRICULTURAL WASTE AS A FEEDSTOCK FOR BIOFUELS IN A BIOREFINERY CONTEXT

The worldwide growing population has led to a rise in production of agricultural products. However, the amount of agricultural waste is increasing daily as a result of agricultural products increase. The production of agricultural waste in large quantities pollutes the environment and leads to several issues with contamination. Therefore, these wastes require a sustainable management *(Chaichi et al., 2022; Li and Chen, 2020).*

The geographic distribution of various useful agricultural-based biomass (energy crops, residues, and manure) can be observed in Figure 3. As it can be seen, more than half of the biomass in the Europe region comes from Germany, France, Poland, and Spain. The amount of bioenergy produced from agricultural wastes is predicted to double from 2012 to 2030, when it might reach up to 25–30 megatons of oil equivalent (Mtoe) (*Hakkola, 2024).*

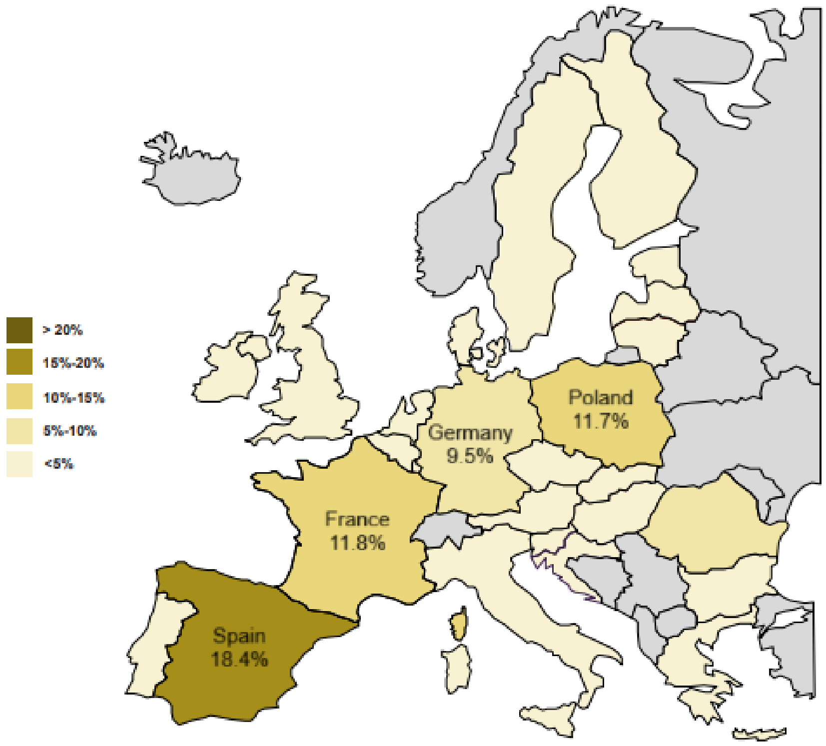

Fig. 3 - Proportion of the potential supply of agricultural biomass (2030) *(Hakkola, 2024)*

Types of agricultural waste

The agricultural wastes can be defined as the residues of agricultural products processing and production. These agricultural wastes can be classified as post harvesting residues or crop residues (such as leaves, husk, straws, and stalks of planted crop which are left after harvest), livestock wastes (bedding materials, animal excrement, and animal fat), industrial processing wastes (such as husk, molasses, bagasse, peels, hulls, seed cakes and pomace) and aquaculture wastes (metabolic wastes, fish wastes, sea weed and algae) (*Iqbal et al., 2021; Pattanaik et al., 2019; Muhammad et al., 2022*). Figure 4 presents the general classification of agricultural wastes.

Post harvesting wastes are produced at the field level by direct agricultural production. Worldwide, around 200 billion tons of crop plant wastes and plant biomass are produced each year, from which 90% is lignocellulosic. Leaf litter, straw, husk, weeds, seed pods, and plant stalks are all examples of post-harvest agricultural waste, which is regarded as primary agricultural waste. The primary component of lignocellulosic waste is the cellulose which represents up 40–50% of the dry weight of plants and is abundant in organic carbon and other plant nutrients (*Duque-Acevedo et al., 2020; Iqbal et al., 2021*). The most available and less expensive organic waste is agricultural residue derived from crop wastes which may be efficiently converted into a variety of products with added value (*Pattanaik et al., 2019*). With over 750 million tons produced annually, corn stalks are the most produced crop waste. Wheat and rice come in second and third place, with 600 and 360 million tons produced annually, respectively (*Muhammad et al., 2022*).

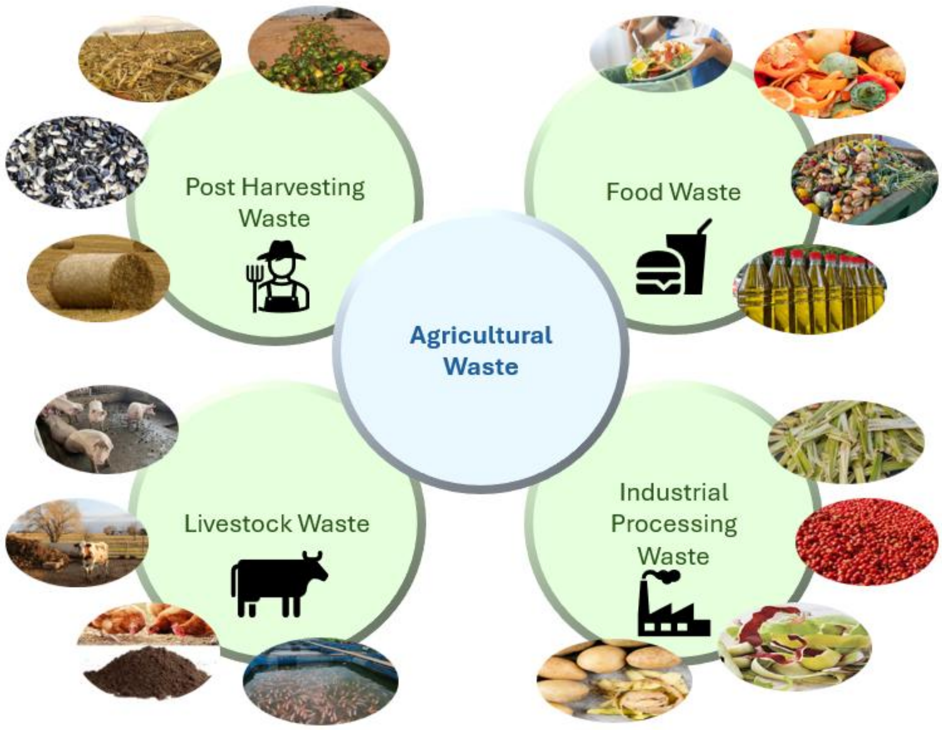

Fig. 4 - Classification of agricultural wastes *(adapted after Muhammad et al., 2022)*

The livestock waste industry generates over 120 million tons of waste per year. This category of agricultural waste mostly consists of waste from slaughterhouses as well as agricultural waste from cattle, pigs, and poultry, consisting of urine, excrement, waste feed, wastewater, feathers, horns, and bedding materials *(Anbesaw, 2022).* Since it primarily comes from cellulosic feed and undigested residue that livestock animal species excrete, animal manure is a renewable resource. Animal excrement is typically applied as fertilizer without being properly treated, which can result in serious environmental issues *(Cantrell et al., 2008*). Manure that has not been treated can seriously pollute the air and water. Wastewater, pathogen contamination, and the leaching of nutrient-rich (mostly nitrogen and phosphorus) liquid manure can all pollute surface waters. However, solid manure contributes to greenhouse gas emissions, which can pollute the air (*Holm-Nielsen et al., 2009*). Aquaculture waste, which includes aquaculture residues like uneaten feed and its fecal waste, has also been recently classified as a subcategory of livestock wastes. Because fish and aquatic plants develop quickly, the aquaculture sector is regarded as one of the fastest-growing food production sectors. The primary source of waste in aquaculture is represented by the feed, followed by fish excrement. Both must be eliminated right away since they are detrimental to fish (*Koul et al., 2022; Dauda et al., 2019).*

Industrial processing wastes represents a category of secondary agricultural wastes, because they are industrial byproducts of primary agricultural waste and waste materials from the production of food. This category of agricultural waste includes peels and pulp from different vegetables and fruits, hulls, molasses from sugar industry, sugarcane bagasse, seed cakes from oil industry, fruit pomace after juice extraction, eggs, chicken skin, and meat from meat industry, etc. (*Bhatia and Sindhu, 2024).* Each year, huge volumes of these wastes are generated. For instance, the sugar production industries produce sugarcane bagasse, of which 180.73 million metric tons are produced annually. Of the 85.84 million tons of fresh fruit produced by the palm plant, over 35.19 million tons of waste are also produced by other industries, such as palm oil (*Sukiran et al., 2017).*

Food waste management is becoming an increasingly significant challenge, as a large portion of it is still disposed of daily in landfills. The biochemical decomposition of such waste generates unpleasant odors and harmful degradation compounds. To counteract these effects, many countries have adopted strategies aimed at reducing consumption and limiting food waste, with the goal of developing a sustainable and environmentally friendly society *(Karmee, 2016).* In this context, biological waste and the organic fractions of municipal solid waste, such as those originating from gardens, households, or the food industry, have gained increasing importance, representing approximately one-third of total waste and constituting a valuable resource for the production of high value-added products. However, the composition of this waste varies significantly depending on factors such as season, harvest period, and the dietary habits specific to each region

(Pandey et al., 2022). Recent research focuses on the valorization of these resources, including bread, wheat, rice, meat, vegetable peels, and mixed food residues, through their conversion into liquid biofuels and other sustainable products *(Karmee, 2016).*

Composition of agricultural waste

Global interest in the conversion of agricultural waste into renewable energy sources has grown considerably in the context of the transition to a sustainable energy system and the urgent need for effective waste management solutions. Recent technological advances allow these waste materials to be exploited as high-potential energy resources. In addition to reducing environmental impact, this approach supports the circular economy by recycling nutrients and reintegrating them into agricultural ecosystems (*Alengebawy, et al., 2024)*.

Agricultural waste resulting from agricultural activities is classified as lignocellulosic biomass, characterized by a complex chemical structure consisting of polymers such as cellulose, hemicellulose, and lignin, along with mineral fractions and extractable compounds, mainly of a protein nature (*Awogbemi and Vandi Von Kallon, 2022; Soni et al., 2023; Ibrahim et al., 2017*).

Cellulose is a structural polysaccharide essential in the formation of cell walls, along with lignin and other components. Due to its long polymer chains, cellulose contributes to the rigidity and mechanical stability of plants *(Garnett et al., 2023)*. Cellulose is the main source of carbon used in the bioconversion processes of lignocellulosic materials, constituting the essential substrate for obtaining various bioproducts *(Tian et al., 2018)*.

Hemicelluloses are a heterogeneous group of polysaccharides found in plant cell walls, together with cellulose and lignin. In wood, the hemicellulose content varies between 10–30%. Unlike cellulose, hemicelluloses have a less uniform chemical composition, hydrolyze more easily, and are soluble in dilute sodium hydroxide solutions *(Grigore, 2016)*.

Lignin is a phenolic polymer with a complex three-dimensional structure that acts as a binder between cellulose fibers, being present in both cell walls and intercellular spaces *(Garnett et al., 2023)*. The relative proportions of lignin, hemicellulose, and cellulose vary depending on the type of biomass and directly influence its energy potential *(Grigore, 2016)*.

Lignocellulose is a complex polysaccharide that requires pretreatment for delignification in order to release the cellulose and hemicellulose fractions suitable for hydrolysis (Figure 5) (*Kaur et al., 2022; Patinvoh et al. 2017*).

Pretreatment is a necessary step in the process of converting biomass into biofuels, involving the disruption of the lignin matrix and the destruction of the crystalline structure of cellulose, in order to transform it into a substrate accessible to enzymes. Thus, the pretreatment of lignocellulosic biomass is an essential step in obtaining sugars from such biomass, with the aim of breaking down the recalcitrant structure of lignocellulose and facilitating the access of hydrolytic enzymes to carbohydrates *(Duque et al., 2017).* The main limitations of current pretreatment technologies are high costs and the difficulty of obtaining a pretreated product with minimal degradation of components.

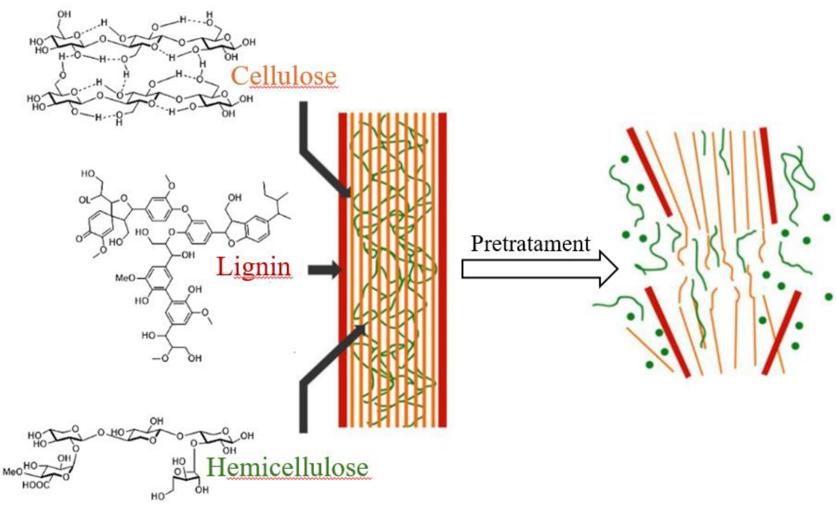

Fig. 5 - Pretreatment of lignocellulosic biomass for separation into cellulose, hemicellulose, and lignin fractions
(adapted after Ikram ul Haq et al., 2021)

Pre-treatment can be carried out using physical methods (size reduction, microwaves, pyrolysis, non-thermal irradiation), chemical methods (wet oxidation, acids, alkalis), physicochemical methods (steam, ammonia, CO_2 explosion), or biological methods (microbial treatments with specialized fungi) (*Kaur et al., 2022*).

The main types of pretreatment are presented below, divided into distinct categories:

- ***Physical Pretreatments*** comprise processes that reduce the particle size of biomass, increase the specific surface area and accessibility for enzymes and microorganisms, decrease the crystallinity of cellulose, and increase conversion efficiency. In general, these methods do not generate inhibitory compounds *(Meneses-Quelal and Velázquez-Martí, 2020; Sikiru et al., 2024).* The main techniques include: mechanical pretreatment (grinding, extrusion); thermal pretreatment and ultrasonic pretreatment. Although effective, these methods are often energy-intensive and costly, limiting their industrial use *(Sikiru et al., 2024)*.
- ***Chemical Pretreatments*** use various compounds, such as acids, bases (alkalis), organic and inorganic compounds, and ionic liquids, that act on the polymer bonds of organic components. This pretreatment increases the biodegradability of biomass and reduces hydraulic retention time *(Sikiru et al., 2024)*.
- ***Biological Pretreatments*** involve the degradation of lignin by aerobic bacteria, fungi, or enzymes, facilitating the conversion of lignocellulosic biomass into valuable products *(Ikram ul Haq et al., 2021)*. This pretreatment has the advantage of not generating toxic substances and requiring low energy consumption. In biological pretreatment, the use of multiple enzymes is essential to increase the efficiency of biomass degradation. Although there is a wide range of fungi with potential in this process, the most commonly applied include the following species: *Phanerochaete chrysosporium*, *Trametes versicolor*, *Ceriporiopsis subvermispora*, *Pleurotus ostreatus*, *Ceriporia lacerata*, *Pycnoporus cinnabarinus*, *Cyathus cinnabarinus*, *Bjerkandera adusta*, *Ganoderma versceumum*, *Irpex lacteus* and *Lepista nuda*, as well as species from the genera *Sporotrichum*, *Aspergillus*, *Fusarium* and *Penicillium* *(Meneses-Quelal and Velázquez-Martí, 2020)*. In general, biological pretreatments are less expensive, but they are characterized by low speed and require large spaces and strictly controlled environmental conditions to ensure increased application efficiency *(Meneses-Quelal and Velázquez-Martí, 2020*).

Each method of biomass pretreatment has specific advantages and limitations, so that a single, cost-effective, and environmentally friendly technology capable of ensuring complete delignification has not yet been identified *(Baruah J., 2018)*. However, pretreatment of lignocellulosic biomass by steam explosion allows for the recovery of 45–65% of xylose, which gives this method a significant economic advantage *(Neves et al., 2007*).

The advantages and disadvantages of the main biomass pretreatment techniques are shown in Table 1.

Table 1

Strengths and limitations of the main biomass pretreatment methods

Pre-treatment method	Strengths	Limitations	References
Physical pretreatment	- Simple operation - Allows handling of large biomass volumes - Increases surface area - Reduces cellulose crystallinity - No chemical use involved - Enhance enzyme digestibility	- High energy consumption - May require additional pretreatment - Unable to degrade lignin - Costly process	*Anukam & Berghel, 2020; Awogbemi & Kallon, 2022; Di Domenico et al., 2025*
Chemical pretreatment	- Alters lignin structure - Hydrolyzes hemicellulose into various sugar fractions - High delignification rate - Short reaction time	- High cost of chemicals - Corrosion issues with equipment - Potential formation of inhibitory compounds - Environmental pollution	*Zhao et al., 2022; Apriani et al., 2020; Awogbemi & Kallon, 2022*
Biological pretreatment	- Low energy consumption - Simple equipment - Efficient degradation of cellulose and hemicellulose - Economic viability - Environment friendly - Mild process conditions	- Very slow hydrolysis rate - Time-consuming process - Low efficiency - Long pretreatment time	*Awogbemi & Kallon, 2022; Woźniak et al., 2025*

Agricultural waste

Agricultural waste represent a potential resource for the development and production of biofuels *(Jamil et al., 2024)*. Crop residues include plant parts left in the field after harvesting, such as stalks, leaves, and roots. They are abundant mainly in cereal crops like wheat, corn, and rice, and accumulate in large quantities during seasonal peaks, especially in cereal-producing regions *(https://www.bindropdumpsters.com/waste-management/agricultural/)*. Currently, wheat straw is mainly used as animal feed, bedding material, or agricultural amendment. However, its conversion into bioenergy remains limited. Burning this type of agricultural residue is not a sustainable solution, as it generates significant greenhouse gas (GHG) emissions, with a potentially negative impact on the environment and contributing to air quality degradation *(Kamusoko and Mukumba, 2024)*. According to *Kamusoko and Mukumba, (2024)*, wheat straw is rich in cellulose and hemicellulose, while lignin is present in lower proportion. It also contains proteins, essential minerals (calcium and phosphorus), silica, ash, bioactive compounds, and vitamins. These characteristics make it a suitable substrate for obtaining bioethanol. Table 2 summarizes the main constituents of agricultural residues *(Tufail et al. 2021; Panpatte and Jhala, 2019)*.

Table 2

The main constituents of agricultural residues *(Ursachi, 2022; Zielińska and Bułkowska, 2024; Karrabi et al., 2023; Tian et al., 2018; Baruah et al., 2018; Panpatte and Jhala, 2019; Kamusoko et al., 2024; Tufail et al., 2021)*

Lignocellulosic biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Corn stalks	37-38	22-26	17-18
Corn cobs	42-45	31 –38	12-15
Wheat straw	27-55	11-37	7-30
Rice straw	31-47	19-32	5-24
Rye straw	31-38	22-37	18-25
Barley straw	31-45	22-38	14-19
Oat straw	30-39	27-30	5-18
Sorghum	32-45	18-28	14-22

Livestock waste

Livestock waste, such as manure and other biological residues resulting from animal husbandry activities on farms (cattle, pigs, and poultry), is another valuable resource. It can improve soil fertility and can be used as feedstock for biofuel production *(https://www.bindropdumpsters.com/waste-management/agricultural/; Hakkola, 2024).* Table 3 shows the main constituents of livestock residues.

Table 3

The main constituents of livestock residues

(*Ludfiani et al. 2024; Saady et al., 2021; Verma et al., 2023; Meneses-Quelal and Velázquez-Martí, 2020)*

	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Paunch content of cattle	22.50	33.80	3.30
Paunch content of goat	23.50	10.80	18.30
Paunch content of sheep	19.70	16.60	15.70
Buffalo feces	31.19	21.03	11.97
Cattle feces	14-35	10-32	9-26
Pig manure	11-33	14-22	1-19
Poultry manure	5-44	9-26	1-9

Industrial waste

A different category of waste is industrial waste, resulting as by-products of various industrial sectors such as meat, fish, dairy, vegetable oil, cellulose, sugar, and fruit and vegetable processing. These materials are often landfilled, incinerated, composted, or converted into biofertilizers. However, they also have valuable potential as raw materials for the production of biofuels due to their cellulose, hemicellulose, and lignin content (Table 4) *(Adetunji et al., 2023).*

Table 4

The main constituents of fruit and vegetable residues

Food waste	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Potato peel	17-55	10-15	5-14	*Agarwal et al., 2022; Soni et al., 2023*
Tomato	30-32	5-26	24-30	*Agarwal et al., 2022; Pirozzi A. et al., 2022; Hijosa-Valsero et al., 2019*
Carrot	13-70	12-19	14-15	*Agarwal et al., 2022; Surbhi et al., 2018*
Apple pomace	7-43	4-24	15-23	*Escudero-Curiel et al. 2023; Kumar et al., 2020*
Banana peels	27-34	9-21	4-8	*Escudero-Curiel et al. 2023; Hamzah et al., 2019*
Orange peel	19- 37	11 -14	7 – 7.5	*Escudero-Curiel et al; Tsipiras et al., 2022*
Olive pomace	8-23	9-29	21-38	*Escudero-Curiel et al; Gómez-Cruz et al., 2024*
Sugarcane bagasse	32-44	27-32	19-24	*Karp et al. 2013*

Table 5 presents the impact of different pretreatment methods on biofuel production from agricultural waste.

Table 5

Impact of pretreatment methods on biofuel production from agricultural waste

Type of waste	Type of pretreatment	Biofuel produced	Results before pretreatment	Results after pretreatment	References
Wheat straw	Biological - ligninolytic fungi	Methane	78.1 NmL gVS^{-1}	396.1 NmL gVS^{-1}	*Shah and Ullah, 2019*
Wheat straw	Chemical - ammonia, 0.70%; 105 °C	Methane	407.8 NmL gVS^{-1}	538.1 NmL gVS^{-1}	*Wang et al., 2019*
Wheat straw	Physical – roll milling	Methane	237 NmL gVS^{-1}	287 NmL gVS^{-1}	*Victorin et al., 2020*
Wheat straw	Physical – milling + Chemical - alkali pre-treatment	Methane	48 NmL gVS^{-1}	290 NmL gVS^{-1}	*Reilly et al., 2015*
Wheat straw	Physical – hammer mill + Chemical - potassium hydroxide	Biogas	1400 mL	20006 mL	*Memon and Memon, 2020*
Wheat straw	Chemical - alkaline pre-treatment (0.5% NaOH)	Biogas	32.2 mL	281.9 mL	*Jankovičová et al., 2022*
Maize waste	Chemical - alkaline pre-treatment (0.5% NaOH)	Biogas	51.3 mL	226.9 mL	*Jankovičová et al., 2022*
Corn stover	Biological – microbial consortia	Biogas	15.820 mL	19.726 mL	*Zhao et al., 2019*

Biofuels and biorefinery concept

Global population growth, lifestyle changes, and high living standards have led to an increase in global energy consumption, with crude oil remaining the main resource for the production of fuels and numerous chemicals. However, the rapid depletion of oil reserves and the negative effects of greenhouse gas emissions (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) on the global climate have generated significant interest in the development of accessible and sustainable renewable energy sources capable of reducing dependence on fossil fuels and their impact on the environment *(Suhag et al., 2015).*

In this context, the comprehensive use of biomass to produce biofuels and value-added compounds, known as the biorefinery concept, has gained particular importance. While biomass was initially used mainly for the production of biofuels as an alternative to fossil fuels, in recent decades the focus has shifted towards the development of a wider range of products, such as biomaterials, fine chemicals, and biopolymers with the aim of improving both the sustainability and economic viability of the industry. These developments suggest a gradual transition from a petroleum-based economy to a bioeconomy, in which biomass becomes the main resource. According to the definition of International Energy and Bioenergy Agency (IEA) task 42, the biorefinery represents "sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, and chemicals) and energy (fuels, power, and heat)" *(Botero et al., 2017).* Figure 6 presents the agricultural waste valorization in a circular bioeconomy system.

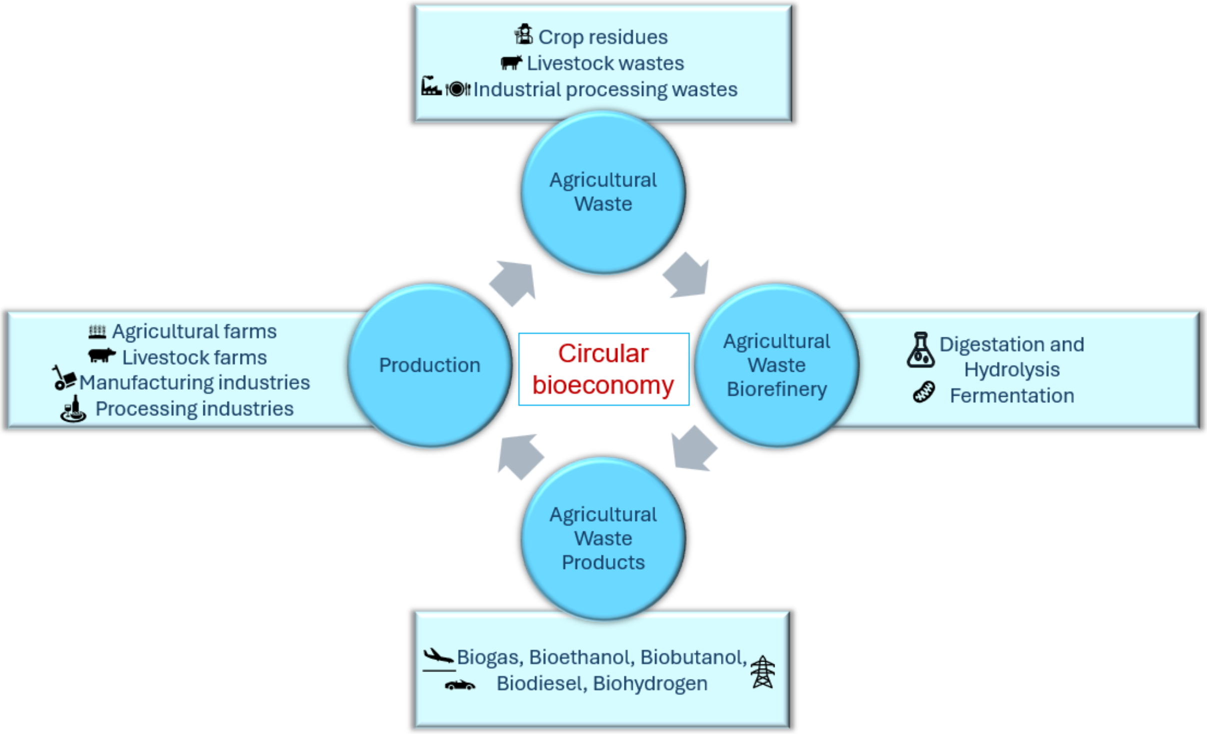

Fig. 6 - Agricultural waste valorization in a circular bioeconomy system *(adapted after Tsegaye et al.,2021)*

To ensure sustainable agricultural development, policies need to be reoriented towards the principles of "reduce, reuse, recycle, and regenerate" *(Rana et al., 2024).* In this context, agricultural waste is a valuable and sustainable resource for generating added value, and its efficient recovery can facilitate the integration of the agricultural sector into the circular economy. The biggest challenge in the successful implementation of an integrated and sustainable biorefinery based on agricultural waste is the development of efficient and economically feasible conversion technologies. Numerous studies report the production of high value-added products from raw materials such as lignocellulosic biomass, algal biomass, food waste, microbially treated waste, and manure, within the modern concept of biorefinery *(Awasthi et al., 2022).*

Lignocellulosic biomass is emerging as a possible source of renewable energy, especially forestry and agricultural waste, paper waste, and energy crops *(Zhang et al., 2010).* Since it is the most frequent type of biomass on the planet, lignocellulose can be used to successfully replace fossil fuels and prove to be a valuable feedstock for the biorefinery method of producing chemical goods and liquid fuels in a sustainable way.

Sugar crops like sugar cane, sugar beet, or sweet sorghum are used in sugar-based biorefineries because they contain high levels of saccharose that are easily removed from the plant material and fermented to produce ethanol or other bio-based compounds.

Enzymatic hydrolysis of starch-rich crops like corn, wheat, and cassava can provide a sugar solution that can then be fermented and turned into chemicals and fuels. As byproducts of processing numerous starch crops, good animal feed that is high in proteins and energy is also produced. In order to produce several useful products, including ethanol, butanol, and wood plastic composites, sweet sorghum stems were investigated in a biorefinery (*Yu et al., 2012).* Oilseeds offer a special chance to produce high-value fatty acids and biofuel, which can take the place of petroleum-based supplies of detergents, lubricants, and specialty chemicals.

Another viable substitute feedstock for biorefineries is algae biomass (such as micro-algae, seaweed, and blue-green algae), due to its significantly higher oil content, productivity, and photosynthetic efficiency *(Singh et al., 2011).* Microalgae have recently gained attention as a promising energy crop for the generation of liquid biofuel because of their high biomass productivity and capacity to develop in wastewater and low-quality water (*Jena et al., 2011).* In the context of biorefineries, microalga *Nanochloropsis sp*. has been shown to be a promising biomass feedstock for the synthesis of fatty acids for biodiesel, biohydrogen, and high-value chemicals. The leftover biomass from the microalga could be utilized as a substrate for a fermentation process to create hydrogen once the oils and pigments have been extracted *(Nobre et al., 2013).* In an integrated biorefinery, red seaweed *Gracilaria verrucosa* algal pulp was used to make agar and bioethanol *(Kumar et al., 2013).*

In biorefinery systems two platforms, thermo-chemical and biochemical, are used to convert biomass feedstock and to promote various product pathways. The thermo-chemical platform concentrates on thermochemical conversion processes, namely gasification and pyrolysis, which employ heat and chemical agents to transform biomass into forms that are more energetically beneficial *(Pravat et al., 2011).* According to Carvalheiro et al., the fundamental processing phases in thermo-chemical platforms are (i) feedstock preparation (drying and size reduction), (ii) biomass conversion by feeding, gasification, and/or pyrolysis, and (iii) product delivery with cleaning and conditioning *(Carvalheiro et al., 2008).* A significant portion of recommended lignocellulosic biorefinery approaches is predicated on biochemical conversion platforms, which use fermentation and enzymes to transform lignocellulosic materials into liquid biofuels, lignin bio-products, and other extractive products. Due to their accessibility, abundance, and cost effectiveness lignocellulosic biomass bioconversion to bioethanol has attracted a lot of interest. Pretreatment, enzymatic hydrolysis, fermentation, and product recovery are the fundamental processes in this method of converting lignocellulosic resources into bioethanol (*Balat, 2011*).

Microorganisms are used in certain biological processes, including dark fermentation, photo-fermentation, and two-stage AD, to hydrolyze lignocellulose and produce residual effluents that are high in volatile fatty acids (*Righetti et al., 2020; Greses et al., 2020*). VFAs are used as raw materials to be further transformed into polyhydroxyalkanoates and derivatives. Biopolymers can be made from these valuable bio-based compounds. The global market for PHAs accounted for 4.8% of the production of bioplastics (105,000 tons) in 2023; according to predictions, by 2028, this percentage is predicted to rise to 13.5% (*Bioplastics Market Development Update, 2023*). PHA is used as a component of many different bioplastics due to its diverse range of qualities. Renewable biomass sources, including vegetable fats and oils, corn starch, straw, wood chips, sawdust, and recycled food waste, are used to make bioplastics (*Quilez-Molina et al., 2023*). They are generated by a number of chemical and biological processes that convert these biomass sources into polymers that can be used to make plastics *(Sen and Baidurah, 2021)*. The bioplastics are used to obtain a wide range of products, such as straws, bags, utensils, packaging materials, and electronic and automotive parts.

The biochar is a solid carbon-rich product which is obtained by pyrolysis process of the biomass, meaning the heating of biomass over 250 °C under limited oxygen conditions. Forest debris *(Yrjälä et al., 2022)*, rice husk and bagasse *(Asadi et al., 2018; Campos et al., 2020),* corncob *(Wijitkosum and Jiwnok, 2019),* olive pits, olive *(Campos et al., 2020*), and other waste materials are used to make biochar. Biochar has gained attention because it may be used in many different fields, for example: as a soil amendment *(Vijay et al., 2021*); an effective sorbent for the reduction of contaminants in soil and water *(Qiu et al., 2022*); a suitable element for gas adsorption applications, such as CO_2 capture *(Karimi et al., 2022*) and H_2 storage *(Yeboah et al., 2020)*; a cheap and renewable fuel in direct carbon fuel cells *(Hao et al., 2022*) and a suitable anode material in microbial fuel cells (*Song et al., 2023*); a potential material for supercapacitors (*Qin et al., 2020)*; a perfect base for activated carbon production (*Xiang et al., 2020*).

The hydrochar is a carbon-rich solid with characteristics similar to coal which is obtained by converting wet organic wastes (the liquid fraction of digestate) through the hydrothermal carbonization (HTC) technology (*He et al., 2022*). The HTC process operates under temperature of 180 ˚C - 250 ˚C and high pressure for several hours, simulating natural coal formation but significantly accelerating it up (*Pauline and Joseph, 2020*). The hydrochar can be used in various applications, such as solid fuel for electricity generation or in industrial processes, efficient medium in water and air purification, component into building materials, plastics, and composites (*Putra et al., 2020; Sharma et al., 2020; Mong et al., 2024*).

Lignocellulosic biomass is converted into pentoses and hexoses, which can then be used as precursors for obtaining a wide range of platform chemicals (*Zielińska and Bułkowska, 2024*).

A platform chemical is defined as a compound that can serve as a basic substrate for the synthesis of high value-added products. Platform chemicals are fundamental elements of the chemical industry and are widely used in the manufacture of food and pharmaceutical products. In 2004, the Department of Energy (DOE) identified a set of 12 essential chemical components derived from biomass that are considered potential platform chemicals. These include ethanol, furfural, isoprene, 2,5-furandicarboxylic acid, hydroxymethylfurfural, glycerol, succinic acid, lactic acid, 3-hydroxypropionic acid/aldehyde, levulinic acid, sorbitol, and xylitol. Most of these compounds, with the exception of glycerol and isoprene, can be produced from biomass-derived carbohydrate sources. Globally, the market for bio-based products was estimated at over $250 billion in 2012, and chemicals derived from renewable resources accounted for approximately 9% of total global chemical sales *(Takkellapati et al., 2018)*. The catalytic conversion of pentosans into furfural, which has significant commercial potential, is one method of processing waste biomass that is rich in hemicellulose. The global market value of furfurals was estimated at $662 million in 2023, and projections indicate growth to approximately $767 million by 2028 *(Global Furfural Market, 2024)*. Polyphenolic compounds found in agricultural waste, particularly in distillery stillage, winery and olive mill waste, presents important uses in the food, cosmetic, and pharmaceutical sectors due to the antioxidant properties. The biobutanol industry produces a variety of valuable byproducts like solvents, fibers, coatings, and plastics, and also acts as a base for compounds like butyl acetate and acrylic acid *(Blasi et al., 2023)*.

Agricultural waste is a valuable source of raw material for cellulose extraction, which is further used to obtain cellulose-based nanomaterials and nanocomposites. Nanocomposites and nanomaterials are widely used in agriculture, medicine, and the food packaging industry. This is due to the remarkable properties of nanocellulose, which converts nanocellulose-based structures into sustainable solutions for superabsorbent hydrogels production, photovoltaic devices, and systems for energy storage, mechanical energy harvesters or catalyst components *(Wang et al., 2017)*. Cellulose nanoparticles can be produced from several types of agricultural wastes *(Gallegos et al., 2016)*. The primary substrate for the synthesis of cellulose nanoparticles and nanocomposites is wheat straw, which is the second-largest lignocellulosic material in the world *(Riseh et al., 2024)*. Rice straw, algae, and sugarcane bagasse are examples of other substrates.

The selection of the product to be obtained in a biorefinery is based on the type of raw material available and its current market price, which directly influences the economic feasibility of the process *(Louw et al., 2023)*. The biological products obtained in a biorefinery must be competitive on the market to ensure the economic sustainability of the process. In this regard, the development of a sustainable biorefinery involves the simultaneous production of high value-added bioproducts and bioenergy in an integrated system *(Takkellapati et al., 2018)*.

BIOFUEL PRODUCTION FROM AGRICULTURAL WASTES

The global energy and food deficit threatens socio-economic activities and negatively affects the sustainable development of society *(Elsayed et al., 2020*). At the same time, the level of development of any country's energy sector has a major influence on the state of its economy, its economic growth rate, the state of the environment, the resolution of social problems, and the standard of living of its population *(Pryshliak and Tokarchuk, 2020)*. Due to growing concerns about greenhouse gas emissions, biofuels have become an increasingly important source of energy resources, to the detriment of fossil fuels. Research conducted in this field has shown that biofuels can be produced from various biomass sources, thus providing a sustainable and environmentally friendly alternative to meet the ever-increasing demand for energy (*Sharma et al., 2020; Pravat, 2017; Hirani et al., 2018*).

There are four generations of biofuels, depending on what kind of raw material is used to make them (Figure 7).

The first generation is based on edible biomass, which is controversial because it competes for significant amounts of food. The second generation is based on non-edible biomass but is limited by industrial scale crops due to high costs. The third generation uses microorganisms as raw material, while the fourth generation attempts to genetically optimize microorganisms to achieve higher yields and at the same time contribute to reducing emissions by producing artificial carbon sinks (*Alalwan et al., 2019)*.

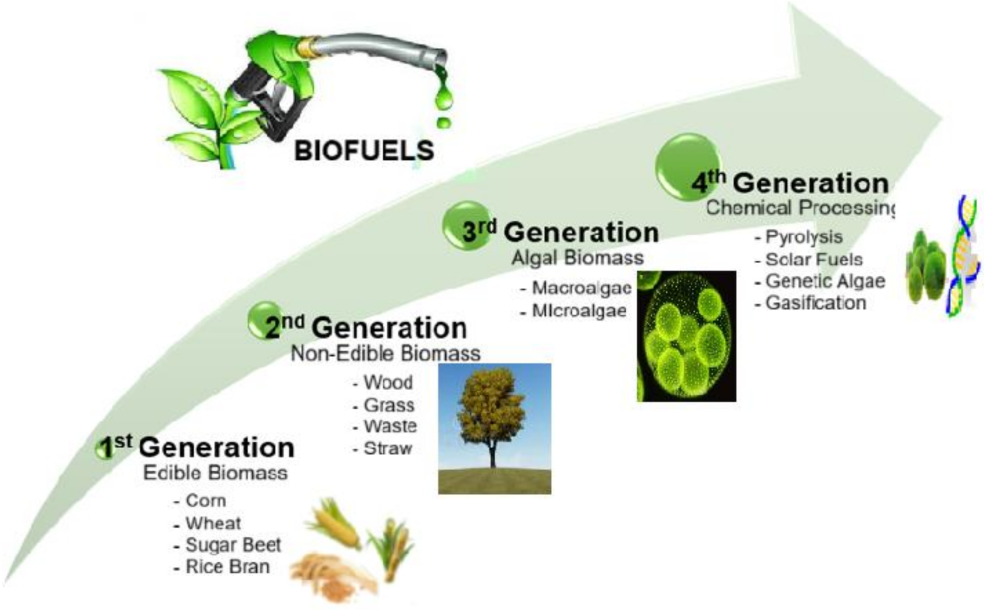

Fig. 7 – Generations of biofuels *(adapted after Alalwan et al., 2019)*

The agricultural sector is one of the most significant sources of waste. Annual agricultural waste production is estimated at approximately 998 million tons, of which biological waste accounts for 80% *(Raut et al., 2023)*. Agricultural waste, generated mainly from farming activities and food processing, is essential for sustainable alternatives to traditional fossil fuels *(Rame et al., 2023)*. Utilizing this agricultural residue for biofuel production presents a practical approach to address both the increasing need for renewable energy and the issue of waste management, as it serves as the primary source for generating second-generation biofuels (Figure 8) *(Kumar et al., 2022).*

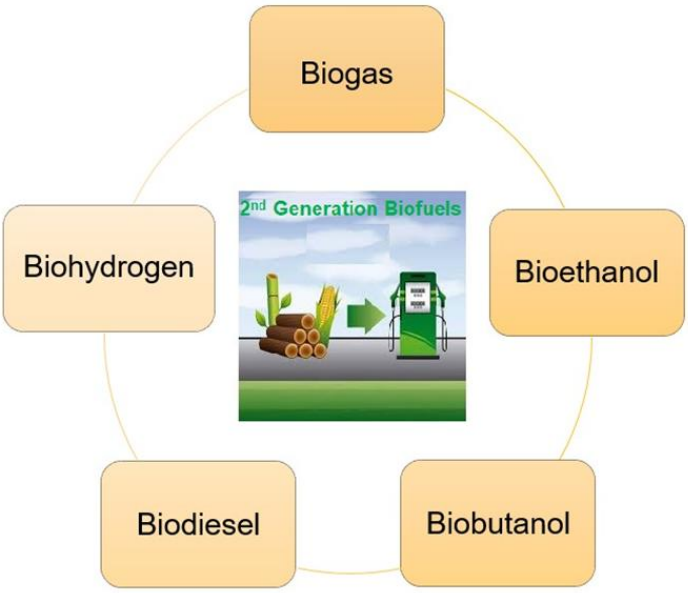

Fig. 8 - Second-generation biofuels *(adapted after Kumar et al., 2022)*

Biogas

Biogas is one of the most important types of biofuels obtained from agricultural waste, playing a significant role in the circular economy and in reducing greenhouse gas emissions *(Alengebawyet al., 2024)*. This gas is a result of the anaerobic degradation of organic matter and is one of the oldest methods used for waste management *(Chen et al., 2012; Mateescu and Constantinescu, 2011).* Over time, the anaerobic digestion process has proven to be effective in treating organic waste from the agro-industrial sector, as well as sludge derived from wastewater *(Streche et al., 2016)*.

The process of obtaining biogas is relatively slow, considering that it is carried out by a group of microorganisms and is influenced by various factors (pH, temperature, HRT, C/N ratio, etc*.) (Hussien et al., 2021*). It has been concluded that in addition to generating energy in the anaerobic digestion process, the other secondary by-products resulting from the process have the potential to be transformed into high-value products, contributing to the transition to a bio-circular economy *(Kapoora et al., 2020)*. Due to these issues, the biogas sector has been rapidly growing in Europe, as evidenced by the 18,843 biogas plants operational in 2021, compared to 6,507 in 2009, according to a report published by the European Biogas Association *(EBA, 2022)*. Furthermore, according to studies conducted, it has been determined that agro-industrial waste contains higher levels of carbon and nitrogen, which increases biogas production *(Oladejo et al., 2020).*

By using waste in an agricultural-scale anaerobic digestion system, researchers at the University of Maryland found that approximately 2,000 MWh/year of renewable energy was produced, enough to power nearly 190 homes, plus 4,200 tons of compost. In addition, greenhouse gas emissions were reduced by approximately 81% compared to other traditional methods of waste manageme*nt (Mahoney et al., 2024).* In 2022, *Alengebawy and collab.* studied the environmental impact of using rice straw in bioenergy production through anaerobic digestion, gasification, and briquetting. The results showed that all these techniques significantly reduce emissions compared to traditional methods, such as burning straw at the production site *(Alengebawy et al., 2022).* Also, in a study on the anaerobic degradability of various Egyptian agricultural residues, it was found that they produced biogas yields ranging from 303 to 496 mLN gVS^{-1} *(Scherzinger et al., 2022).* In addition to the fact that the use of agricultural waste in biogas production contributes to the reduction of greenhouse gases, this also has other advantages such as mitigating the odors emanating from manure *(Jin et al., 2021*) and creating new economic prospects for rural communities *(Meng et al., 2020)*.

Bioethanol

Bioethanol is an alternative to gasoline, reducing greenhouse gas emissions when blended as an additive. It produces approximately 60% of sugarcane and 40% from other types of crops. Research has shown that this sustainable product could reduce CO_2 concentrations by about 90% and sulfur dioxide (SO_2) levels by 60–80% when blended with 95% gasoline, with high octane rating *(Chang and Lin, 2004; Saxena et al., 2009; Lu and Mosier, 2008).* The utilization of agricultural biomass in the form of bioethanol represents an accessible and sustainable source with high potential for commercial bioenergy production*.*

According to studies conducted in this field, it has been established that in the EU the largest quantity of bioethanol is produced from wheat and sugar beet, while in the US cereals (including wheat and corn) are used for bioethanol production, with China producing this product using sweet potatoes, cassava, and yams as substrates *(Gupta and Verma, 2015).* Among the studies conducted in this field, Cherian et al. investigated the fact that MaO_2 improves bioethanol production from sugarcane leaf biomass at optimal parameters *(Cherian et al., 2015).* Studies have shown that microbial agents play an essential role in the fermentation process used for bioethanol production. It has been demonstrated that *Saccharomyces cerevisiae* can efficiently ferment a variety of substrates, including apricot industrial waste, achieving an ethanol yield of 45.69 g/L (*Zoubiri et al., 2020*), while the use of mixed microbial consortia, such as the combination of *S. cerevisiae* and *Candida cantarelli*, has resulted in yields of up to 92.5 g/L from saccharified corn stover *(Kamal et al., 2022).* On the other hand, pretreatment of wheat straw with alkaline peroxide led to almost complete decomposition of lignocellulose (≈ 96.75%) after enzymatic hydrolysis, while pretreatment with organic solvents achieved a lower degradation rate of approximately 75% *(Saha and Cotta, 2006).* By studying different types of bacteria, yeasts, and fungi, and after performing enzymatic hydrolysis of wheat straw with high sugar content, a bioethanol yield of between 65-99% was obtained *(Talebnia and al., 2010)*. Thus, it can be said that bioethanol obtained from agricultural waste is a promising technology, but unlike other types of biofuels, the process involves more challenges, such as the transport and handling of biomass, but also pre-treatment methods for the total delignification of lignocellulose *(Sarkar et al., 2012)*.

Biobutanol

Another second-generation biofuel that contributes to the green energy transition is biobutanol, a biofuel primarily obtained from agricultural waste converted into simple sugars, followed by bacterial fermentation, during which microorganisms such as *Clostridium acetobutylicum* convert the sugars into butanol.

Butanol represents a promising alternative fuel owing to its high energy content, low volatility, and advantageous physicochemical properties, including reduced hygroscopicity and corrosiveness, which enhance its compatibility with existing fuel infrastructure and engine systems *(Ni and Sun, 2009).* This resulting product is technically more advantageous than bioethanol because it has a higher energy density and is mixed more easily with fossil fuels. Some vehicles that use gasoline as fuel can replace it with biobutanol without requiring technical modifications to the vehicle's structure. Biobutanol can be blended with gasoline in proportions of up to 11.5% by volume, with an energy content on average 10–20% lower than that of gasoline. An advantage of biobutanol is that it can reduce CO_2 emissions by up to 85% compared to conventional fuels *(Habeeb, 2012).* A study conducted in 2020 showed that the use of immobilized *Clostridium acetobutylicum* bacterial cells allowed for the production of up to 13.8 g/L of biobutanol from rice straw used as raw material *(Tsai et al., 2020)*, and Moradi et al. showed that pretreated rice straw can attain a biobutanol yield of 81.4–112.7 g biobutanol per Kg *(Moradi et al., 2013).* Similar results were obtained in other studies using alkaline-pretreated sugarcane bagasse, achieving a yield of over 14 g/L of biobutanol *(Pang et al., 2016).* The high potential of agricultural waste for obtaining biobutanol was also demonstrated by the study conducted by Zhang et al., where around 9–10 g/L of biobutanol was obtained *(Zhang et al., 2018).* Another study demonstrated that the conversion of agricultural waste into butanol through alkaline pretreatment, enzymatic hydrolysis, and fermentation processes is feasible, achieving a maximum concentration of 2.29 g/L for bagasse and 2.92 g/L for rice straw *(Cheng et al., 2012).*

Biodiesel

Biodiesel is a renewable, biodegradable fuel made from natural oils or fats (such as vegetable oil, animal fat, or used cooking oil) through a chemical process called transesterification. It consists mainly of fatty acid methyl esters (FAME) and can be used in diesel engines, either pure (B100) or blended with petroleum diesel (e.g., B20 = 20% biodiesel + 80% diesel).

Biodiesel is mainly produced through a chemical reaction called transesterification. This process converts oils or fats (triglycerides) into fatty acid methyl esters (FAME) — which is biodiesel — and glycerol as a by-product.

Agricultural waste for biodiesel mainly includes used cooking oil, animal fat, non-edible oilseeds (like *Jatropha and Pongamia*), fruit seed waste and agro-industrial residues rich in oil.

Among the various technologies for converting waste into biofuels, the most effective method is the conversion and fermentation of starch or sugar residues into ethanol, along with the transesterification of cooking oil waste or animal fat into biodiesel. In examining the economic sustainability of the biofuel production process, factors such as raw materials, technology, product quality, and market acceptance are analyzed. Regarding technological advancements, the production of liquid biofuels has seen more progress compared to the production of solid and gaseous biofuels, due to its greater potential for conversion, reduced waste generation, and lower consumption of water and land. It has also been reported that biodiesel energy constitutes 90% of the volume of diesel energy, whereas the energy volumes of bioethanol and biobutanol are 50% and 80% of gasoline, respectively.

Research has shown that biodiesel made from waste coffee oil possesses remarkable physical and chemical properties. These include higher heating values, elevated flash points, impressive cetane numbers, and favorable acid values. Additionally, it's noted that the pour point and cloud point of this biodiesel can be enhanced through the application of various additives *(Sharma, 2024).* Investing in the production of biodiesel, countries can decrease their dependence on foreign oil markets. This is particularly important for nations that import a significant portion of their energy needs, as it enhances national security. Local production of biodiesel can lead to greater price stability by diversifying energy sources. This reduces vulnerability to fluctuations in global oil prices, resulting from geopolitical tensions or market instability. The biodiesel industry can support the agricultural sector by providing farmers with an additional market for crops. This can lead to increased economic stability in rural areas, making them less reliant on volatile commodity markets.

The biodiesel industry creates jobs in both the agricultural and manufacturing sectors. This boost in employment can reduce economic dependency on imported goods and strengthen local economies. Focusing on renewable energy sources like biodiesel helps countries meet their environmental goals, such as reducing greenhouse gas emissions and combating climate change. This can align with energy policies aimed at sustainability and conservation. A biodiesel industry with 0.16 million tons of capacity per year is located in Sete, France, and is operated using heterogeneous catalyzed process technology. Correspondingly, 8000 MT/annum of biodiesel was industrialized in Malaysia by Biofuel, Ltd., in cooperation with Incbio *(Schill, 2009).*

Incorporating biodiesel into the energy mix diversifies the energy supply, making countries less susceptible to external disruptions. A diversified energy portfolio improves national resilience against supply chain interruptions. Many governments implement policies and incentives to promote the use of biodiesel, such as subsidies, tax incentives, and renewable energy mandates. These frameworks encourage investment and development within the biodiesel sector, fostering greater energy independence. Biodiesel is increasingly used as a fuel for vehicles, railways, aircraft, and power generators. A significant proportion of modern heavy construction equipment and agricultural machinery now operate on biodiesel. Concerns over rising environmental pollution and greenhouse gas emissions, especially from transportation, have further driven interest and investment in biodiesel production. For instance, global biodiesel production increased from 42 billion liters to 43 billion liters in 2021 and is projected to reach an average of 46 billion liters between 2023 and 2025 (figure 9). Correspondingly, the global market value of biodiesel, estimated at USD 46.79 billion in 2021, is projected to rise to USD 51.48 billion by 2026 *(Awogbemi et al., 2022).*

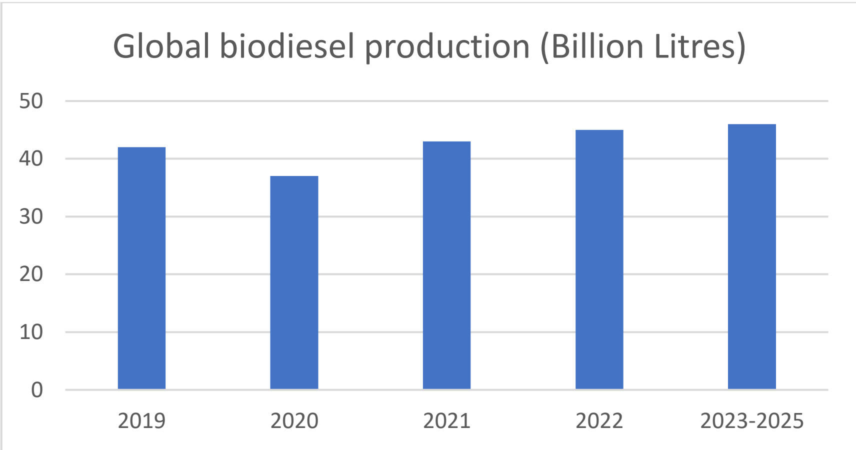

Fig. 9 - Global biodiesel production (Billion Liters) *(Awogbemi et al., 2022)*

Biodiesel is an eco-friendly, renewable diesel substitute made from natural oils and fats. It reduces pollution, promotes sustainability, and can be used in existing diesel engines — but cost, feedstock, and cold performance remain challenges.

Biohydrogen

Biohydrogen is a clean, non-toxic, carbon-free, and advanced biofuel derived from biomass through biological and thermochemical methods. It is a colorless, tasteless, odorless, and highly combustible renewable fuel, serving as a sustainable alternative to fossil fuels. With a high energy content of 120–142.9 MJ/kg and a calorific value of 143 GJ/ton, it stands out as the most valuable and preferred among all biofuels. Biohydrogen has a wide range of applications across the transportation, electricity generation, food and beverage, pharmaceutical, and industrial sectors, offering both economic and social advantages, and playing a significant role in the circular economy (Importantly, when used as fuel in internal combustion engines, biohydrogen does not emit CO_2, gaseous pollutants, or other greenhouse gas precursors. Instead, its combustion produces water, thus ensuring ecological integrity and helping to combat climate change. Although the technology for biohydrogen production remains relatively costly and competitive, its reliance on readily available, sustainable, environmentally friendly, and renewable biomass provides it with a competitive advantage over other renewable fuels *(Awogbemi et al., 2022*).

Biohydrogen can be generated through various biological pathways, which can be broadly classified into two main categories: light-dependent and light-independent processes. Light-dependent processes encompass direct or indirect photolysis and photo-fermentation, while dark fermentation represents the primary light-independent process *(Zhang et al.,2017*). Direct photolysis utilizes the photosynthetic abilities of algae and cyanobacteria to directly split water into oxygen and hydrogen. The advantage of direct photolysis lies in its use of water as the main feedstock, which is both abundant and inexpensive.

The production of biohydrogen occurs through the direct absorption of light and the transfer of electrons to two types of enzymes: hydrogenases and nitrogenases. In anaerobic conditions or when excessive energy is captured during the process, certain microorganisms release the surplus electrons by employing a hydrogenase enzyme that converts hydrogen ions into hydrogen gas. Reports indicate that the protons and electrons obtained from the water-splitting process are recombined by a chloroplast hydrogenase to produce molecular hydrogen gas with a purity level reaching up to 98% *(Show et al., 2012).*

Hydrogen serves as a carbon-free fuel, releasing only water vapor as a byproduct during combustion. According to the Global Hydrogen Review 2021 *(IEA, 2021)*, the rising demand for hydrogen production and the shift towards cleaner technologies in transportation fuel are critical steps toward achieving Net Zero Emissions. Hydrogen and hydrogen-based fuels have the potential to prevent up to 60 gigatons of CO_2 emissions between 2021 and 2050, accounting for approximately 6.5% of total cumulative emission reductions during this period.

The use of biotechnological approaches is viewed as crucial for achieving sustainable and competitive biohydrogen production within the clean and green renewable energy sector. As a result, the scope of research now encompasses a variety of innovative technologies. These include the development of advanced engineering designs for reactor modification, improvements in feedstock utilization, greater understanding of microbial communities, applications of metabolic or genetic engineering (such as hydrogenase modification), and the enhancement of post-fermentation downstream processes, particularly the purification of hydrogen by eliminating contaminants like CO_2, H_2S, and N_2 *(Ramprakash et al., 2022).*

Governments worldwide primarily emphasize medium- and heavy-duty transportation, with Japan and Korea placing significant focus on the future of automobiles. While fewer nations are exploring synthetic fuels for aircraft decarbonization—Germany recently issued a power-to-liquids (PtL) roadmap—or integrating hydrogen into rail transport, many are considering hydrogen and ammonia's potential in the shipping sector. Japan has taken a notable step by releasing an Interim Report from the Public-Private Council on Fuel Ammonia, which outlines the introduction of ammonia as a fuel for shipping and energy generation (IEA 2021*) (Sharma et al., 2022; Zheng et al.,2021)*

Currently, there are 16 carbon capture, utilization, and storage (CCUS) systems active in generating hydrogen from fossil fuels, yielding approximately 0.7 million tons of hydrogen annually. By 2030, this production is expected to increase significantly to over 9 million tons per year, driven by an additional 50 projects under development. With over 80% of the global CCUS hydrogen production capacity, Canada and the United States are the leading producers in this sector. However, the United Kingdom and the Netherlands are working to challenge their dominance, with the majority of upcoming projects currently in the planning phase according to data from the IEA in 2021*) (Sharma et al., 2022; Zheng et al.,2021).*

Solubilizing food waste (FW) through diverse pretreatment methods prior to biohydrogen production represents a cutting-edge strategy with significant financial potential. The selection of a pretreatment method typically depends on the specific composition of the FW. Each method comes with its own set of benefits and limitations. In summary, current pretreatment techniques could be optimized to enhance their efficiency, ultimately resulting in improved biohydrogen production rates *(Banu et al., 2019).*

Another method of valorizing agricultural waste is its conversion into solid biofuels, in the form of pellets and briquettes. The main categories of biomass that can be used for this purpose come from a wide range of sources, including agricultural residues (e.g., rice straw, corn stover, corn cobs and husks, wheat straw, rice husks, but also sugarcane stalks), forest biomass, energy crops, municipal solid waste, and industrial waste *(Saravanan et al., 2023; Güleç et al., 2023)*. Pellets and briquettes produced from agricultural waste are commonly known as agri-pellets *(Paraschiv et al., 2017)*. The calorific value, chemical composition, and moisture content are similar for both materials; however, pellets exhibit higher density and mechanical strength *(European Biomass Industry Association, 2021; Gageanu et al., 2021).* Overall, the quality of briquettes and pellets is influenced in part by the characteristics of the substrate (moisture content, particle size, and biomass composition) and by the process parameters (die temperature, pressure, and geometry) *(Gageanu et al., 2021; Gageanu et al., 2016; Voicea et al., 2014).* The calorific value of agricultural pellets ranges between 12 and 18 MJ/kg, and the ash content is relatively high (over 1%) (*Smaga et al., 2018).*

Thus, densification of lignocellulosic biomass also supports the principles of the circular economy by reducing waste generation and lowering greenhouse gas emissions.

AGRICULTURAL WASTE VALORIZATION FOR BIOFUEL PRODUCTION: A BIBLIOMETRIC ANALYSIS

Research Methodology

To examine the research landscape on *agricultural waste, valorization,* and *biofuel production*, a bibliometric study was undertaken with the aim of providing both a quantitative overview and a qualitative interpretation of developments in this field. Bibliometric analysis was selected because of its capacity to trace the structural evolution of a research domain, identify thematic clusters, and highlight key contributors through systematic data evaluation.

The literature search was performed in September 2025 using the Web of Science Core Collection (WoS), a database recognized for its rigorous selection criteria and its wide acceptance in the academic community as a reliable source of peer-reviewed publications. Keywords were carefully selected and refined through preliminary trials; the final search string incorporated the terms *"agricultural waste"*, *"valorization"*, and *"biofuel production"*. These terms were applied to the *Topic* field, which encompasses titles, abstracts, author keywords, and Keywords Plus, in order to capture a comprehensive and representative dataset.

The initial search returned **201 records**. In line with the objective of ensuring consistency and reliability, publications from the year 2025 were excluded, given that the year was still ongoing and indexing was incomplete at the time of analysis. This adjustment reduced the dataset to **167 records**. A further refinement was applied to remove non-article materials such as editorial notes, meeting abstracts, and retracted papers. After applying these filters, a final dataset of **162 scientific articles** was established as the foundation for the analysis.

All records were exported in plain text format with complete metadata, including author information, affiliations, source journals, abstracts, keywords, funding acknowledgments, and citation counts. This format ensured compatibility with bibliometric software and allowed for in-depth exploration of research patterns.

The analysis addressed several dimensions of the field, including:

- the temporal evolution of publications concerning agricultural waste valorization and biofuel production;
- the distribution of document types (e.g., journal articles, conference papers, review articles);
- the most prolific authors, institutions, and countries contributing to this domain;
- the co-occurrence of keywords, shedding light on conceptual linkages and thematic clusters.

The bibliometric mapping was carried out using **VOSviewer**, which generated network visualizations of keyword co-occurrence and author collaborations. These analytical tools were crucial in identifying established research trajectories, highlighting underexplored areas, and outlining emerging themes relevant to the sustainable valorization of agricultural waste into biofuels.

Research findings and discussion

Figure 10 reflects the temporal distribution of the 162 analyzed publications that has a clear upward trajectory in research addressing agricultural waste valorization and biofuel production. Early contributions were sporadic and exploratory, often confined to laboratory-scale assessments. However, beginning in the mid-2010s, the number of publications increased significantly, reflecting the broader global commitment to renewable energy and circular bioeconomy strategies. The peak in 2022, followed by a slight decline in 2023 due to incomplete indexing, highlights the consolidation of this research domain into a mature field of inquiry. The observed growth trajectory underscores the relevance of agricultural waste valorization as both a scientific challenge and an industrial necessity. This trend highlights how academic production often mirrors policy momentum and industrial interest in agricultural waste valorization for biofuel production.

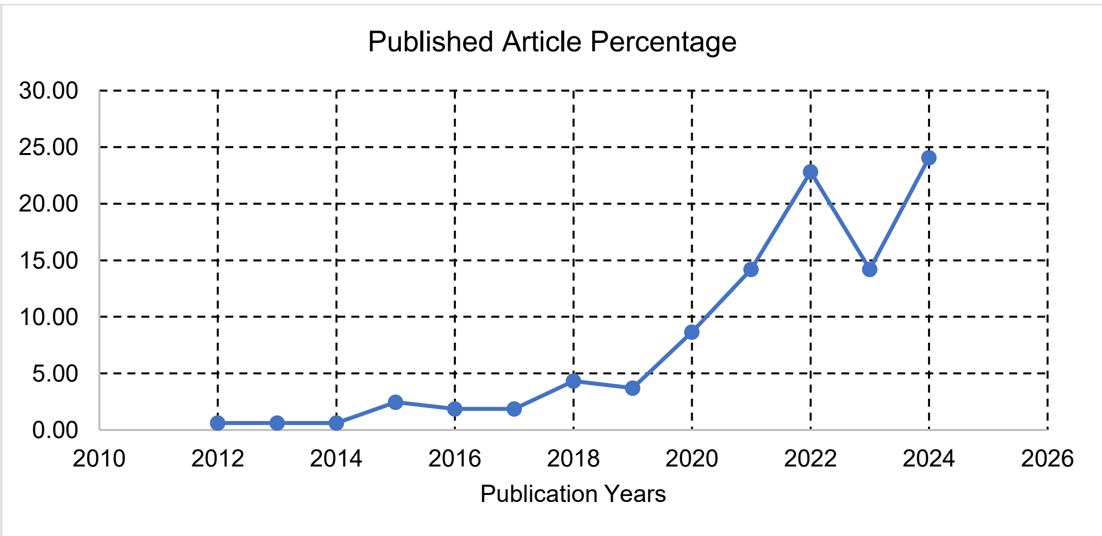

Fig. 10 - Diachronic productivity published in Web of Science *(own creation)*

Analysis of document types (Figure 11) shows that journal articles dominate the scientific output, accounting for over 53,29 % of the publications. Reviews represent the second largest category, indicating a growing effort to synthesize knowledge, identify gaps, and establish frameworks for future exploration. Conference proceedings and book chapters remain less represented, but their presence suggests ongoing knowledge exchange within professional communities. This distribution reflects a research area transitioning from methodological experimentation towards consolidation and theoretical refinement.

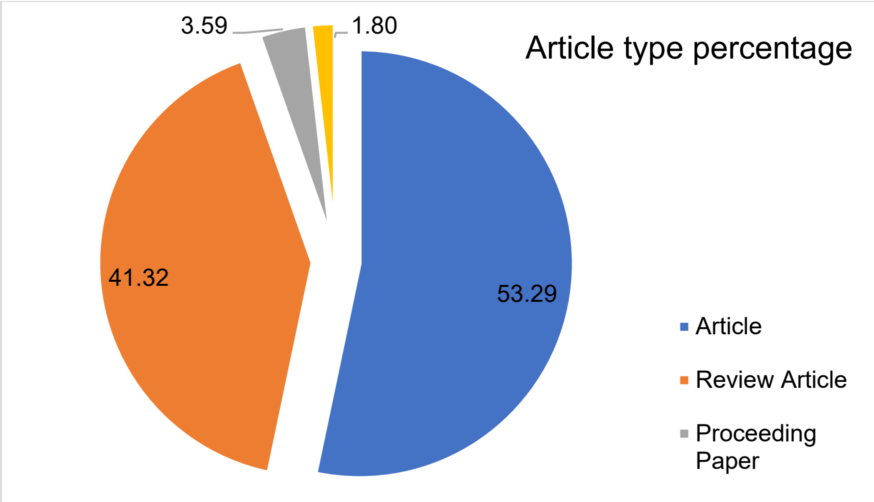

Fig. 11 - Document type published by scientists in the timeline of the analysis *(own creation)*

The analysis of publication outlets highlights the interdisciplinary character of research on agricultural waste valorization and sustainable biofuel production. Table 6 presents the top ten journals that collectively account for a significant share of the 162 articles examined. The results indicate that Energies (MDPI) emerge as the most prominent journal, publishing eight articles on the topic. Although its impact factor (3.2) and CiteScore (7.3) are moderate compared to other outlets, its open-access model and broad thematic scope make it an attractive platform for disseminating applied energy research. High-impact journals such as Renewable and Sustainable Energy Reviews (Elsevier, IF = 16.3, CiteScore = 38) and Bioresource Technology (Elsevier, IF = 9, CiteScore = 20.7) also appear in the ranking, each contributing seven publications. Their inclusion underscores the scientific maturity and global relevance of this field, particularly in the context of renewable resources and waste-to-energy pathways. Similarly, Science of the Total Environment (Elsevier, IF = 8, CiteScore = 16.4) demonstrates the environmental dimension of agricultural waste valorization, integrating sustainability and ecological impact assessment.

Journals with a strong thematic alignment, such as Biomass Conversion and Biorefinery (Springer Nature, IF = 4.1) and Biomass & Bioenergy (Elsevier, IF = 5.8, CiteScore = 11), reflect the technical focus on biomass transformation processes. Meanwhile, Waste and Biomass Valorization (Springer Nature, IF = 2.8) reinforces the role of circular economy approaches in energy recovery. Finally, specialized and emerging outlets like Fermentation (MDPI, IF = 3.3, CiteScore = 5.7) and Fuel (Elsevier, IF = 7.5, CiteScore = 14.2) capture niche areas of this research domain, ranging from bioconversion pathways to combustion technologies. Overall, the distribution of publications across journals reveals a balance between high-impact interdisciplinary outlets and domain-specific platforms, suggesting that the field is simultaneously advancing fundamental knowledge and offering practical solutions. The presence of journals with strong environmental and sustainability profiles further indicates that the valorization of agricultural residues is increasingly framed as both an energy innovation and a strategy to address global ecological challenges.

Table 6

Top 10 scientific journals published on “agricultural waste”, “valorization”, and “biofuel production” ranked by the number of publications

Rank	Journal	Publisher	Number of publications	Impact factor	CiteScore
1	ENERGIES	MDPI	8	3.2	7.3
2	BIOMASS CONVERSION AND BIOREFINERY	Springer Nature	7	4.1	
3	BIORESOURCE TECHNOLOGY	Elsevier	7	9	20.7

Rank	Journal	Publisher	Number of publications	Impact factor	CiteScore
4	RENEWABLE SUSTAINABLE ENERGY REVIEWS	Elsevier	7	16.3	38
5	SCIENCE OF THE TOTAL ENVIRONMENT	Elsevier	7	8	16.4
6	SUSTAINABILITY	MDPI	7	3.3	7.7
7	BIOMASS BIOENERGY	Elsevier	6	5.8	11
8	WASTE AND BIOMASS VALORIZATION	Springer Nature	6	2.8	
9	FERMENTATION BASEL	MDPI	4	3.3	5.7
10	FUEL	Elsevier	4	7.5	14.2

When linking the publisher distribution (Figure 12) to the journal analysis presented previously (Table 4), a clear consistency emerges between the most prolific journals and their corresponding editorial groups. *Elsevier* dominates with 73 publications, which directly reflects the strong representation of its flagship journals such as *Bioresource Technology*, *Renewable & Sustainable Energy Reviews*, *Journal of Cleaner Production*, and *Biomass and Bioenergy*. These journals also appeared prominently in the earlier ranking, confirming Elsevier's central role in advancing research on biomass valorization and sustainable energy.

MDPI, accounting for 34 publications, follows as the second-largest contributor. Its presence is largely explained by open-access journals like *Energies*, *Sustainability*, and *Fermentation*, which were also identified in the top 10 journals. The prominence of MDPI in both the table and the figure underscores the increasing influence of open-access publishing in this research domain.

Springer Nature ranks third with 29 publications, supported primarily by *Biomass Conversion and Biorefinery* and *Waste and Biomass Valorization*, both of which were identified among the most relevant journals. This publisher's contribution highlights the importance of interdisciplinary outlets that focus on applied bioresource and conversion technologies.

The smaller but notable contributions of *Taylor & Francis*, *Royal Society of Chemistry*, *Wiley*, and *WIT Press* (each below five publications) reveal that while these publishers are less dominant, they provide complementary spaces for niche and specialized studies, often with a more chemical or environmental engineering focus. Finally, the *Others* category, with 14 publications, shows the presence of smaller or regional journals, though these remain peripheral compared to the core publishing houses.

Taken together, the alignment between the table and the publisher distribution chart reinforces the observation that a small group of powerful publishers—primarily Elsevier, MDPI, and Springer Nature—concentrate the majority of scientific discourse in this field. Their dominance suggests that future research visibility and impact are strongly tied to these editorial channels, while smaller publishers may play a role in diversifying methodological approaches and perspectives.

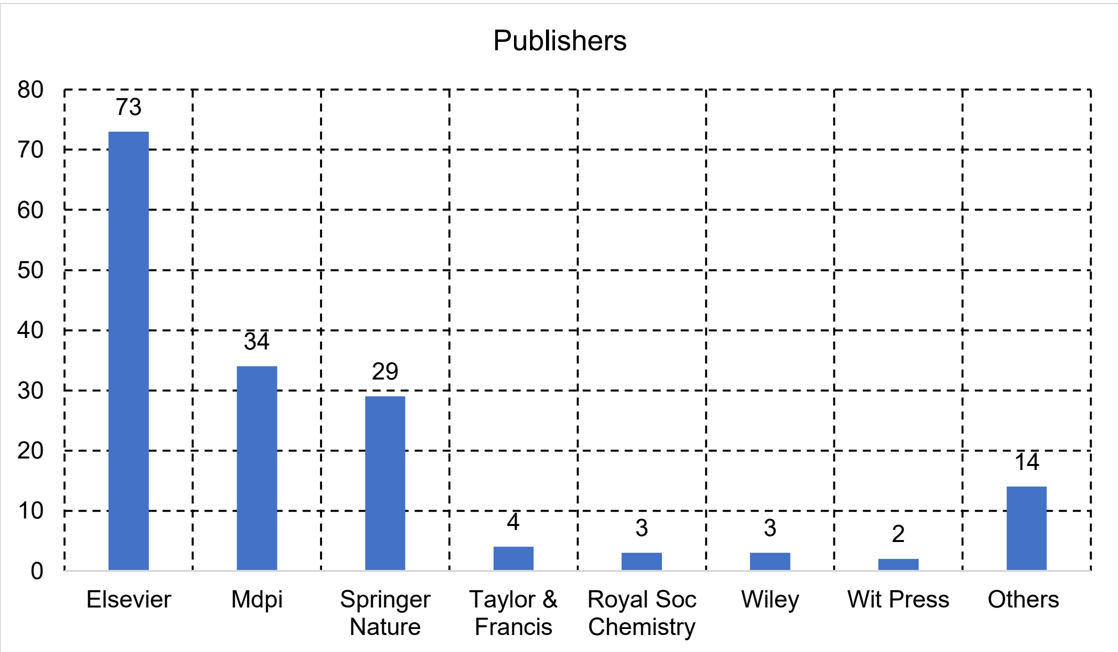

Fig. 12 - Top Publishers ranked by the number of publications

The keyword co-occurrence analysis offers an in-depth overview of how concepts related to agricultural waste, biomass valorization, and biofuel production are thematically interconnected (Figure 13). By applying VOSviewer, six major clusters were identified, each capturing distinct yet interrelated dimensions of the research field (Figure 14).

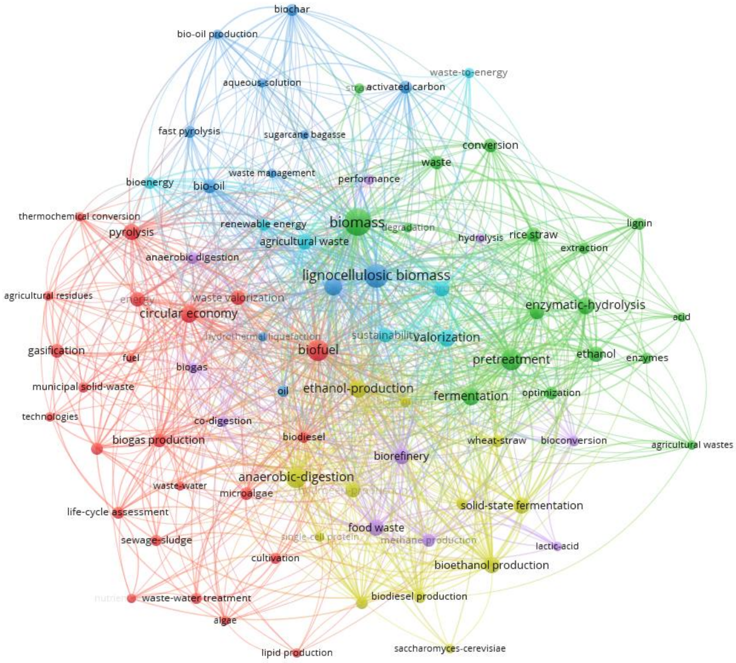

Fig. 13 - Co-occurrence network of using all keywords as a unit of measure *(own creation)*

Cluster 1 (Red, 23 items): This cluster groups terms such as *agricultural residues, biofuel, circular economy, cultivation, gasification, pyrolysis, sewage sludge,* and *wastewater treatment*. The emphasis here lies on resource recovery strategies and waste-to-energy pathways. The integration of circular economy principles suggests an increasing focus on sustainability and life-cycle assessment in bioenergy systems *(García-García et al., 2020).* The presence of *pyrolysis* and *gasification* underscores the importance of thermochemical conversion routes for valorizing biomass and waste streams into energy carriers.

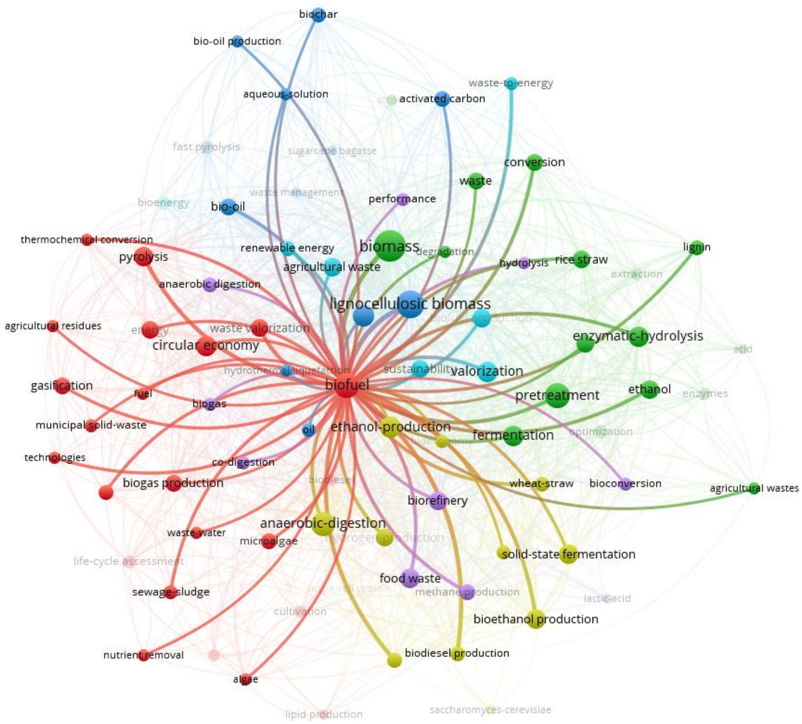

Fig. 14 - Network of the main cluster *(own creation)*

Cluster 2 (Green, 17 items): This cluster is dominated by terms like *enzymatic hydrolysis, pretreatment, lignin, rice straw, conversion, and ethanol*. It reflects the scientific interest in the biochemical processing of lignocellulosic biomass for advanced biofuel production. The prominence of *enzymatic hydrolysis* and *pretreatment* highlights ongoing efforts to overcome recalcitrance and enhance sugar recovery from complex biomass structures (*Kumar & Sharma, 2017; Zhao et al., 2020*). Agricultural residues such as *rice straw* are commonly examined feedstocks, reinforcing the role of low-cost, abundant resources in developing scalable biofuel solutions.

Cluster 3 (Blue, 12 items): This cluster includes *biochar, bio-oil, fast pyrolysis, hydrothermal liquefaction, sugarcane bagasse,* and *activated carbon*. It emphasizes thermochemical pathways and the valorization of by-products for energy and material applications. The frequent appearance of *biochar* and *activated carbon* illustrates the growing interest in environmental co-benefits, particularly carbon sequestration and pollutant removal, alongside energy recovery (*Hernández-Mena et al., 2017; Hoang et al., 2022*).

Cluster 4 (Yellow, 12 items): Keywords such as *biorefinery, biodiesel production, biohydrogen production, solid-state fermentation,* and *single-cell protein* represent this cluster. It captures the diversification of biorefineries beyond traditional liquid biofuels into high-value bioproducts. The integration of *biohydrogen* and *single-cell protein* reflects the broadening scope of biorefineries to encompass both energy vectors and alternative protein sources, reinforcing the multi-product potential of biomass valorization.

Cluster 5 (Purple, 10 items): This cluster revolves around *anaerobic digestion, co-digestion, food waste, lactic acid, methane production,* and *biogas*. It highlights the centrality of anaerobic digestion as a mature, widely adopted technology for waste valorization. Co-digestion strategies, often combining agricultural waste with food residues or sewage sludge, are prominent, as they enhance process efficiency and biogas yields *(Mata-Alvarez et al., 2011).* Furthermore, the inclusion of *lactic acid* and *bioconversion* points to the potential of integrated biogas systems for producing biochemicals alongside energy (*Lian et al., 2020).*

Cluster 6 (Light Blue, 7 items): Containing keywords like *sustainability, renewable energy, bioenergy, agricultural waste,* and *valorization*, this cluster links the technical advances of biomass utilization to broader environmental and societal objectives. It represents the overarching thematic framework of the field, where biofuel production is framed within the global transition toward decarbonization and sustainable energy systems *(Abdel-Shafy & Mansour, 2018; Awatshi et al., 2022).*

The six clusters reveal the **multi-dimensional nature of research on biomass valorization**. The field is structured around both **biochemical (enzymatic hydrolysis, fermentation)** and **thermochemical pathways (pyrolysis, gasification, hydrothermal liquefaction)**, while cross-cutting themes such as *circular economy*, *sustainability*, and *biorefinery integration* ensure the research is oriented toward real-world applications.

The prevalence of *biofuel* and *circular economy* as high-frequency and high-linkage keywords confirms that the discourse is no longer restricted to energy generation alone but increasingly incorporates systemic approaches to waste valorization. Moreover, the co-occurrence of *biorefinery* with terms such as *biohydrogen* and *single-cell protein* reflects an evolution toward **next-generation biorefineries** capable of producing both energy and value-added co-products.

Finally, the diversity of clusters indicates an ongoing trend toward **interdisciplinary convergence**: chemical engineering, microbiology, environmental science, and energy policy perspectives are all represented, underscoring the complexity and relevance of biomass valorization for sustainable development.

CONCLUSIONS

1. When efficiently managed and valorized, agricultural waste has the potential to become a sustainable resource for producing biofuels and other value-added products, thus enhancing energy security, supporting the circular economy, and protecting both the environment and human health. Moreover, due to their high content of organic matter, the efficient management of agricultural waste is an important factor in promoting the sustainable development of agriculture.

2. Biofuels represent a sustainable alternative to fossil fuels, offering solutions to the global energy crisis and contributing to environmental protection. Agricultural and organic waste provide significant potential as renewable raw materials for second-generation biofuels, supporting the circular economy and efficient waste management.

3. Biogas, bioethanol, biobutanol, biodiesel, and biohydrogen derived from agricultural and industrial residues can substantially reduce greenhouse gas emissions while promoting rural economic growth and energy security. Overall, the conversion of biomass and agricultural waste into diverse biofuels contributes to

cleaner energy systems, waste reduction, and sustainable socio-economic development. Continued research and technological innovation—particularly in microbial engineering, catalytic processes, and large-scale optimization—are essential to enhance production efficiency, reduce costs, and accelerate the transition toward a low-carbon global energy system.

4. This bibliometric study provides an integrated view of the scientific landscape on agricultural waste valorization for sustainable biofuel production. By examining 162 publications indexed in Web of Science, the analysis highlights consistent growth in the field, with research distributed across high-impact and specialized journals such as *Energies*, *Bioresource Technology*, and *Renewable and Sustainable Energy Reviews*. The presence of multiple publishers and outlets underscores the interdisciplinary nature of the topic, spanning energy systems, environmental sciences, and biotechnology.

5. Keyword co-occurrence and cluster mapping revealed six major research domains, ranging from biochemical conversion and thermochemical valorization to integrated biorefineries, anaerobic digestion, and sustainability-driven frameworks. The prominence of these clusters demonstrates both the technical depth and the broad applicability of agricultural waste in the energy transition. At the same time, the dispersion of research efforts across different approaches suggests the importance of greater methodological convergence and stronger international collaboration.

6. Overall, the findings confirm that agricultural residues represent a vital resource in advancing sustainable biofuel pathways. Future work should place greater emphasis on energy efficiency, life-cycle sustainability, and technology scalability, ensuring that scientific advances translate effectively into industrial practice and contribute to global climate and energy objectives.

ACKNOWLEDGEMENT

This research was funded by National University of Science and Technology POLITEHNICA Bucharest through the PubArt program.

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