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ABSTRACT

The management of agro-food waste (AFW) is a pressing environmental, social, and economic issue. Owing to the large and heterogeneous production in Italy, which is one of the EU's leading agricultural producers and food processors, it is crucial to effectively manage the AFW in terms of reduced emissions, costs, and lower resource consumption. The management of these wastes could be carried out by considering them as a resource for high-value compounds and (bio)energy. This review offers an overview of AFW management processes according to circular economy principles, by exploring available technologies at different Technology Readiness Levels (TRLs), focusing on the Italian context. The review provides descriptions of industrial-scale and pilot-scale plants, as well as emerging biological approaches for converting AFW into high-added valuable compounds and energy. This approach promotes the inclusion of AFW within a circular economy framework, increasing the sustainability of waste management by considering them as valuable resources.

1. Introduction

For a long time, the utilisation of natural resources, food, and energy has been performed according to the linear economy model based on the concept of "take-make-dispose". However, this model is no longer adoptable as the global population is projected to reach 9 billion people by 2050 [1]. The Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) reported that in 2019 almost 40 % (i.e., 4.8 billion hectares) of the Earth's habitable land surface was used for agriculture. Of this land, one-third was designated as cropland, accounting for 1.6 billion hectares, and the remaining two-thirds consisted of permanent meadows and pastures utilized for livestock, with 3.2 billion hectares in total [2]. Between 2000 and 2021, the global production of primary crops reached 9.5 billion tons [3] with a consequential increase in the quantities of agricultural waste. Hence, shifting from a linear to a circular model is strictly necessary to preserve resources, manage waste, and guarantee sustainable development for the next generations [4].

The circular economy is a regenerative model based on reduce-use-recover-recycle-redesign-remake, which offers a framework that aligns with the Sustainable Development Goals (SDGs) of Agenda 2030. When the circular economy integrates a circular loop into a product's life cycle, it revolutionises the idea of product end-of-life by emphasizing the efficient utilization of finite resources. This model promotes a paradigm shift in the concept of waste, which is viewed as a secondary raw material that (partially or fully) substitutes the primary resources (renewable and non-renewable), thereby mitigating the impacts of habitat degradation, land use change, and biodiversity loss.

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A significant component of the circular economy is the bioeconomy, which encompasses biological resources and processes that provide goods and services, including food, energy, and healthcare. In Italy, in 2022, the bioeconomy generated an overall value of € 415.3 billion, employing approximately 2 million people [5]. The bioeconomy concept can be realised through the second-generation biorefinery system, which converts waste biomasses into a spectrum of bio-based products, such as ingredients for feed and food, chemicals, biomaterials, or energy in different forms (fuels, electricity, and heat). Biorefineries allow synergies between different agro-food waste (AFW) and their conversion into high-added-value products [6].

AFW encompasses the waste and by-products of agriculture, food industries, and farms, including crop residues, livestock waste, industrial processing biowaste, and food waste [7]. Annually, global agricultural residue production exceeds 5 billion tons, with Asia being the main producer (47 %), followed by America (29 %), Europe (16 %), Africa (7 %), and Oceania (1 %) [8]. AFW from farmland residues enclose mainly stems, stalks, leaves, seed pods, weeds, cereal straws, bagasse, oil palm biomass, and natural non-wood plant fibres, like bast fibre, and leaf fibre. Livestock waste encompasses a variety of materials including animal excrement, bedding, rainwater runoff, soil, hair, feathers, and other organic matter commonly associated with animal husbandry [7].

The use of AFW as a renewable and readily available local resource has gained importance, although, AFW availability depends on geographical context and seasonality. Italy contributes to European agricultural production by around 14 %. However, for specific sectors, Italian contribution represents 37 % for wine, second only to France (43 %), and 33 % for olive oil, which follows Spain with 48 %. In fruit production, Italy covers 18 % of the EU's production, second to Spain, which covers 28 %. Additionally, Italy leads in pasta and bakery product production in the EU, accounting for 73 % of the total EU turnover.

Historically, Italy has always been divided into three macro zones: the North, the Centre, and the South, with different social, economic, and technological developments. The agricultural land in Italy used for farming and livestock covers an area of 12,856,048 ha (42 % of the total national territory). Northern and Central regions are characterized by a more industrialized landscape, whereas the Southern regions predominantly focus on agriculture and tourism. Despite the socioeconomic disparities between the North and South of Italy, the Southern regions demonstrate considerable potential in renewable energy resources, also from AFW [9]. Implementing bioeconomy principles for AFW management would not only reduce the environmental burden of waste but also enable its conversion into valuable resources (including organic acids, ethanol, biofertilizers, flavours, enzymes, biopesticides, and biologically active secondary metabolites), thus supporting a sustainable agro-food sector [10,11]. Transitioning from a linear to a circular economy within the agro-food sector in Italy requires the adoption of innovative business models, along with new legislation and marketing strategies for customer-supplier relationships that intersect multiple value chains [12]. From this perspective, understanding the portfolio of available processes for converting and valorising AFW is imperative.

2. State of the art and aim of the review

Numerous studies highlighted the potential of converting AFW into valuable products and energy through diverse processes. While existing reviews often address individual processes, many overlook crucial factors such as the practical application and integration of these processes within a specific regional context. This includes considerations of Technology Readiness Levels (TRLs), the availability of facilities in the region, ~~and~~ the analysis and comparison of multiple processes, ranging from lower to higher TRLs. Several reviews focus on a single by-product or do not consider innovative strategies for waste conversion and primarily focus on waste at the household level [13]. Furthermore, they do not correlate their findings with the existing facilities in the territory, which is a crucial aspect [14] in considering the scalability of the process at the industrial waste management scale.

As an example, Boccia et al. [15] investigated innovative strategies for the recycling and valorization of tomato waste within the Italian context, exploring approaches such as bioconversion into biofuels, the production of bioplastics, and the extraction of valuable compounds like lycopene and antioxidants. Despite these contributions, their study does not consider real-industrial examples of commercial exploitation, detailed economic analyses, technological barriers, or comprehensive environmental impact assessments. On the other hand, the studies of Venanzi et al. [16], Tamburini et al. [17], Scano et al., [18], and Di Fraia et al., [19] evaluated the technical, economic, and environmental sustainability of using agricultural by-products as feedstock that can replace dedicate cultures in biogas production in the Umbria and Emilia Romagna (Italian central regions) and Sardinia and Campania (Italian south regions), respectively. However, these individual studies examined by-products available in each region, which may limit the understanding of how similar practices could be implemented in other regions or countries with different by-products. Moreover, their economic analyses are influenced by local policies and subsidies specific to the region while other areas may have different regulatory frameworks or financial incentives that could affect the feasibility and attractiveness of using agricultural by-products for biogas production.

The present comprehensive review advances the current literature by focusing on AFW management strategies in Italy, aiming to understand the deployment and scalability of available processes based on their TRLs. In particular, the review aims to understand how to effectively integrate these multiple processes according to their TRLs by mapping and identifying current facilities in the Italian context and considering available environmental and economic evaluations, based on environmental and economic studies available in the literature.

This review emphasizes the management processes, their technological maturity, and the extent to which these processes are utilized within Italy. The TRL framework employed consists of 9 levels, from early-stage concepts (level 1) to full commercial deployment (level 9), and is used to evaluate both the positive and negative technological, environmental, and economic implications of each process [20]. This review aligns its analysis with the United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (affordable and clean energy), SDG 12 (responsible consumption and production), and SDG 13 (climate action).

Although the term "waste" usually denotes something discarded, the terms "by-product" and "residue" refer to substances that are not a primary aim of a production process. In the present review, they are used as synonyms to indicate processing waste residues (e.g., olive pomace) and inedible biogenic materials (e.g., plant leaves) without distinction, considering their common origin from primary and secondary agricultural sectors. In detail, according to De Corato and Cancellara. [21], the whole AFW system includes agriculture, agro-food industry, distribution, and retail sectors.

The structure of the review concerns the processes divided into 3 groups based on their TRL (Fig. 1): industrial-scale processes (i.e., functioning plants), pilot-scale processes (available to date but undergoing validation), and emerging processes (studied on a laboratory scale but not yet available on a large scale) [20]. By mapping facilities and examining factors such as facility size, type, and distribution, this review provides insights into the real-world application of AFW processes within the Italian context, using data derived from both the current literature and companies websites and both censuses and official Italian documents, such as those from ISTAT (i.e., the Italian National Institute of Statistics) and regional like Arpa (Italian acronymous for the Regional Agency for Environmental Protection). The choice of source largely depended on the maturity of the process. For example, pilot-scale processes were studied considering literature sources (including Science Direct, Web of Science, and Scopus databases) and pilot plant websites. For industrial plants, a combination of peer-reviewed literature,

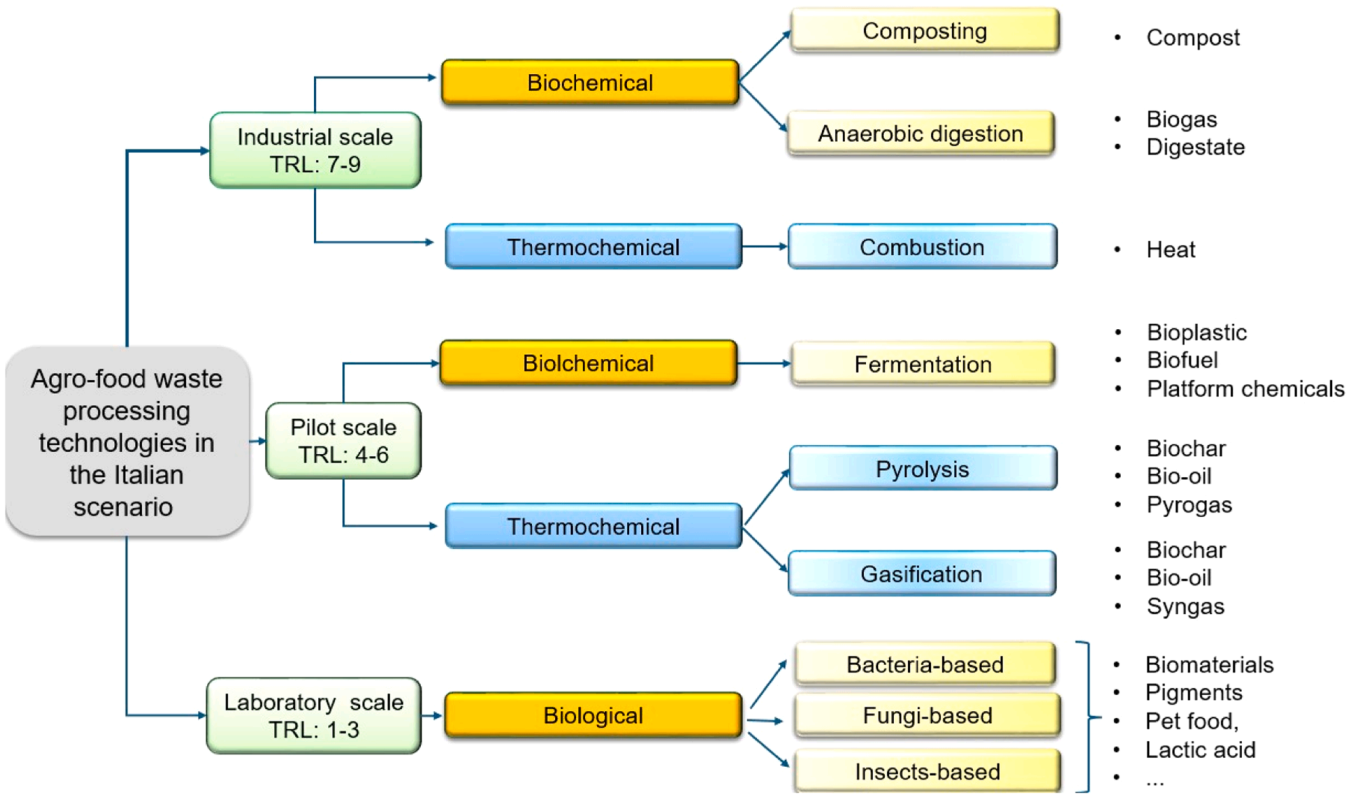

Fig. 1. Scheme of the available technologies clusterised according to their technology readiness level.

government and industry reports, and direct information from plant operators was utilized to ensure accuracy regarding operational performance. Research on emerging technologies primarily involved academic articles and lab-scale study reports to assess their current feasibility and potential for scalability.

3. Industrial-scale processes

Available processes with a high market maturity include composting, anaerobic digestion (often coupled with composting), and combustion (i.e., mass burning for energy recovery). However, these processes are to date mainly used for the management and valorisation of urban solid waste, while little is known about the fraction of AFW used. While the capacity of individual plants is often unavailable, their numbers in Italy are provided annually by ISPRA, i.e., the Italian Institute for Environmental Protection and Research (Fig. 2). Those authorized plants are considered to provide an overview of the scale and distribution of the processes in Italy and could represent a starting point to understand if they could be adopted also to convert AFW into valuable products and energy.

3.1. Composting

Composting is a well-established process for solid organic wastes encompassing the degradation of biodegradable components by microbial communities under controlled conditions [23,24]. The numerous facilities currently in operation demonstrate the maturity of the process leading to the highest technology readiness level (TRL 9). The composting process plays a crucial role in the agro-food sector by converting organic waste into valuable compost, which can then be used to improve soil health in agriculture. Furthermore, the symbiotic relationship between composting and agriculture aligns with the principles of a circular economy, where organic waste is minimised and promotes sustainable and organic farming practices by returning organic matter to the soil. The conversion of organic waste into valuable organic soil amendment (i.e., compost) also contributes to reducing the reliance on synthetic fertilizers. Composted organic waste encompasses high nutrient contents reducing the need for mineral fertilizers to improve the fertigation efficiency [25]. The main advantages and disadvantages of composting are summarised in Table 3.

The quality of the obtained compost mainly depends on both the process parameters (e.g., temperature, availability of oxygen, type of technology, carbon-to-nitrogen (C/N) ratio) and the nature and characteristics of organic waste treated [23]. The moisture content of AFW is generally high, and it may negatively influence the decomposition process leading to anaerobic areas [24]. For instance, the use of tomato plant residues as a single composting feedstock is not recommended due to its low C/N ratio and excess moisture content [26]. To overcome the limitations related to the physicochemical properties of some AFW [27] composting facilities usually combine other fractions such as yard and green waste, organic fraction of municipal solid waste (OFMSW), and sludge from wastewater treatment plants [24] Nowadays, researchers are exploring more sustainable and technically advanced composting systems. Indeed, new processes have been recently developed and they are under investigation to effectively reduce nitrogen loss and increase the nitrogen content of compost products. Among newly developed processes, a membrane-covered composting system is attractive for its capacity to improve oxygen utilization and pile temperature while reducing NH_3 and N_2O emissions. Contrary to open composting systems, this process allows the recovery of ammonia nitrogen resources and consequently prevents the release of harmful emissions [28]. However, membrane-covered composting is still limited to bench/pilot-scale applications due to costs related to membranes and sensors (e.g., for temperature and gas emissions) [29]. Another emerging process is hyperthermophilic composting (HTC), an aerobic fermentation that accounts for the inoculation of hyperthermophilic microbes for raising pile temperatures (>80 °C) and shorter composting time compared to conventional thermophilic composting (~5–7 days without external

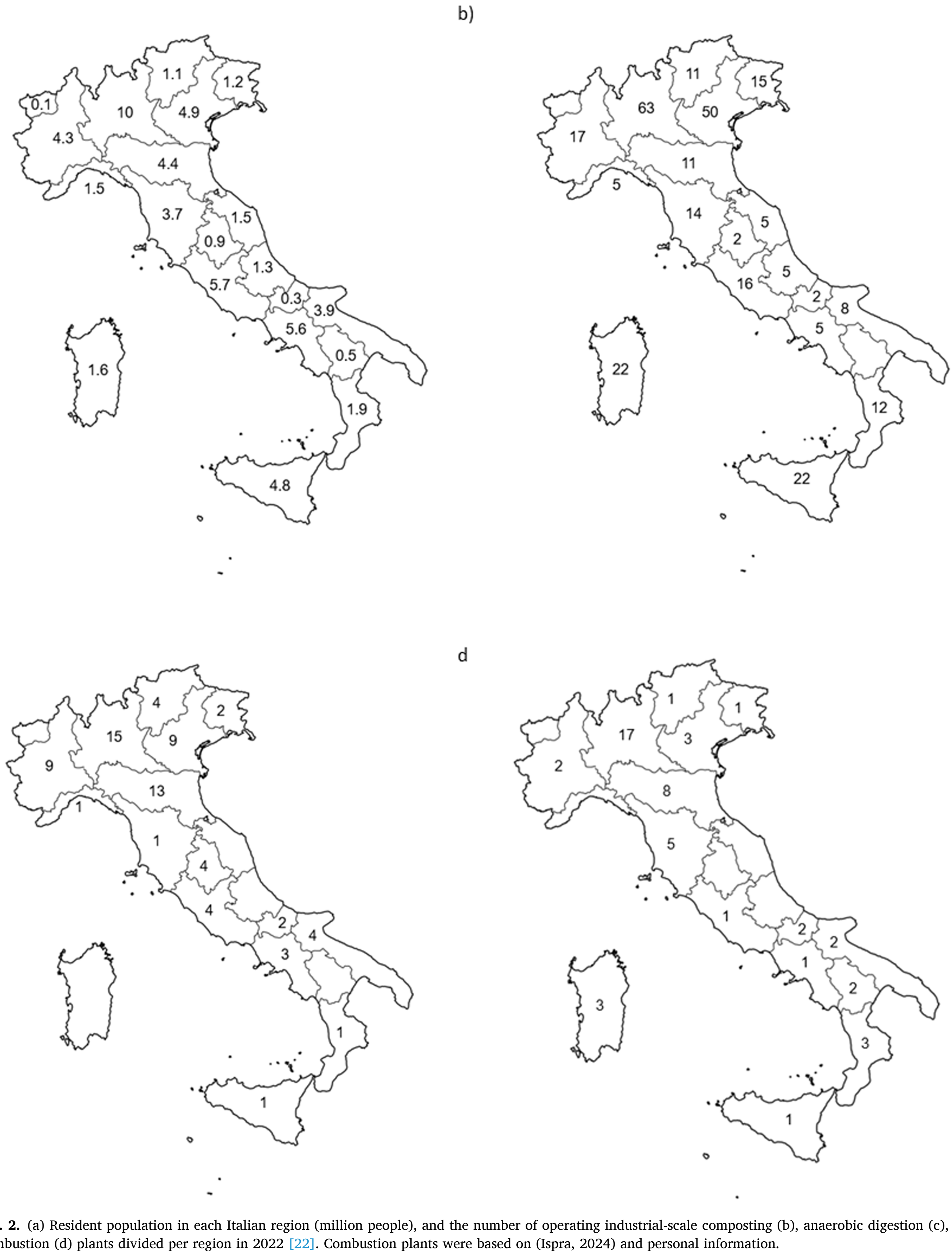

Fig. 2. (a) Resident population in each Italian region (million people), and the number of operating industrial-scale composting (b), anaerobic digestion (c), and combustion (d) plants divided per region in 2022 [22]. Combustion plants were based on (Ispra, 2024) and personal information.

heating) [29]. Consequently, it was pointed out that HTC enhanced organic matter degradation and nitrogen conservation, with a better quality of compost produced also reported in recent studies [30]. To accelerate the degradation process of organic carbon and consequently reduce the maturation time, electric field-assisted composting (EAC) involves the application of an electric field to conventional composting [31]. Consequently, oxygen utilization is improved by activating electroactive bacteria and inducing electron flow to oxygen [31]. This process can potentially promote organic matter degradation while reducing N_2O emissions. However, the industrial applications of EAC are limited due to low electron transfer efficiency, electricity costs, and low electrical conductivity of composting materials [29].

3.1.1. Composting plants in Italy

In Italy, as a result of the rise in separate collections of OFMSW, including yard/green waste and AFW, composting has emerged and strengthened in the last 25 years [32]. This development is proved by the increase in the number of composting facilities. Indeed, comparing the number of running composting plants in 1998 [33] with the number of composting facilities currently in operation (285, based on the latest census of ISPRA conducted in 2022), a significant increase (~72 %) should be highlighted demonstrating the maturity of the technology and its crucial role also in the Italian agri-food sector.

The Italian composting plants (Table 1) are mainly devoted to treating OFMSW (~45 %) mixed with small amounts of other fractions (e.g., yard/green waste (~32 %), AFW). Of the 285 composting facilities in Italy 132 operated with AFW and other matrixes such as yard/green waste. Specifically, Table 1 surveys the Italian composting facilities operated with AFW at an industrial scale. Based on the collected information, the highest number of plants is located in Lombardy (31) followed by Sicily (14) and Piedmont (11). It should be pointed out that the amount of AFW treated (ton/year) in composting facilities is censed with other wastes such as wastepaper, cardboard, wood, waste from industrial sectors (e.g., textile, paper, wood), and waste from aerobic and anaerobic waste treatment. Consequently, an accurate quantification of AFW treated in Italian composting facilities is not feasible. However, to better understand the composition of AFW treated, deepened research was made by looking at the websites of composting companies. The Italian composting facilities process olive pomace, grape stems, tomatoes, straw, and corn. Two plants in Tuscany mainly treated OFMSW, organic residues, and waste from agro-industrial processing cycles (i.e., tomato and grape). Data collected in 2021 revealed that the most treated biomasses are OFMSW (82 tons/day) and lignocellulosic waste (11 tons/day), while the amount of compost produced per day was 15 tons (i.e., 4095 tons/year). In Italy, the composting facilities currently in operation utilize windrow and in-vessel systems. Most facilities primarily rely on naturally vented windrow technology. However, in some regions of Southern Italy, in-vessel systems and biocell bioreactors are the most commonly employed technologies.

According to Italian Legislation (D.Lgs 75/2010 and subsequent amendments), compost is a soil amendment classified into three categories of "End-of-waste" according to the input feedstock: green compost (GWC), biowaste compost (BWC), and sludge compost (SWC).

Table 1
Number of plants, location, and typology of feedstocks used in composting plants in Italy in 2022.

	OFMSW	OFMSW, AFW, and others (*)	AFW and others (*)	Total
North	102	21	49	172
Center	12	7	12	37
South	36	27	13	76
Total	153	55	77	285

AFW, agro-food waste; OFMSW, organic fraction of municipal solid waste; (*): Wastepaper, cardboard, wood, waste from industrial sectors, waste from aerobic and anaerobic waste treatment.

According to the information derived from ISPRA, the highest amount of compost produced in Italy in 2022 is the BWC (446,992 tons/year), followed by GWC (299,755 tons/year) while no plant is currently producing sludge compost. In 2022 the majority of GWC in Italy (~70 %) were produced from composting facilities located in Lombardy (209,219 tons/year) which accounts for 31 plants, followed by 7 plants located in the Emilia-Romagna (20,121 tons/year). Conversely, the 60 % of annual BWC produced was mainly derived from 3 Italian regions: Lombardy, Sicily, and Piedmont which are also the regions with the highest number of plants.

Looking at information reported in the ECN (European Compost Network) Data Report (2022) [34], about 722,000 tons/year of compost produced in Italy were certified under the ECN's Quality Assurance Scheme (ECN-QAS). Furthermore, in European countries (including Italy) an increase in the value of total nitrogen phosphorous and potassium content of ECN-QAS-certified compost was reported from January 2021 to March 2022. Specifically, in Italy, it was estimated that in March 2022 one tonne of certified compost contains nutrients valued at ~80 € per tonne (fresh matter) [34]. This evidence suggests that certified compost is a cost-effective source of NPK plant nutrients. Furthermore, to enhance the development of the biowaste management sector and consequently to improve the quality of the compost produced in Italy, the Italian Composting and Biogas Association (CIC) introduced in 2003 the "CIC Quality Compost Label" (CQL). This label represents an added value to the compost market ensuring a constant increase in the quality of compost. According to CIC information, the amount of BWC and GWC employed in agriculture represented more than 70 % of the total amendments used in this sector in Italy (data referred to 2016) [32].

3.2. Anaerobic digestion

Anaerobic digestion (AD) is a biochemical process by which, in the absence of oxygen, the organic matter contained in plant-based and animal-based materials is converted into digestate and biogas, consisting mainly of methane (CH_4, 55–75 %,) and carbon dioxide (CO_2, 25–45 %). The percentage of methane varies, depending on the type of organic matter digested, the process conditions, the pre- or post-treatment required, and the type of reactor equipment chosen [35]. The process is carried out by a syntrophic consortium of microorganisms (hydrolytic bacteria, acidogenic bacteria, acetogenic bacteria, and methanogenic archaebacteria) and the internal temperature of the digester selects the type and strains of bacteria [36]. The biogas obtained can have several uses: production of heat, production of electricity and heat by cogeneration, and purification (i.e., upgrading) to produce biomethane. The classification method of greatest interest is based on the concentration of total solids (TS) present in the biomass used to feed the digester. In this sense, the AD process is denoted wet (TS$\leq$ 10 %) semi-dry (TS 10–20 %), or dry (TS$\geq$ 20 %) [37]. Waste conversion into energy and fuels by AD processes has the highest TRL (TRL 9) among biochemical processes.

There are potentials for innovation at the level of usage of new substrates and reactors (e.g., two-stage AD processes), monitoring of the biological process, digestate valorization, biogas to biomethane upgrading systems (e.g., capable of producing food-grade CO_2), and optimization of bacterial strains. The substrates that can be used to feed digesters can be grouped into the following main categories according to their sector of origin: dedicated crops (maize, sorghum, etc.), livestock effluents (manure and slurry), agricultural by-products, animal, and vegetable wastes (pomace, citrus pulp, rice husks, etc.), OFMSW, and sewage sludge [38]. The biogas yields obtainable from individual biomasses are, however, a function of their chemical and physical characteristics. This is attributable to the varying biodegradability of organic compounds and the possible presence of refractory and/or inhibiting substances, which require pretreatment of the matrices before start-up in anaerobic reactors [39]. Biogas production is an excellent way to use organic waste for energy production, followed by the reuse of the digestate as fertilizer, which is rich in nutrients and microelements [40]. Additional emissions also result from the operation of biogas plants, the use of biogas, and the transport and disposal of digestate [41]. The digestate is separated into liquid and solid parts in most AD facilities. While the liquid portion is either processed in a wastewater treatment plant or recirculated inside the plant, the solid fraction is administered directly to farm fields as a mineral fertilizer or composted to produce a soil improver. Integrated anaerobic/composting treatment plants are indeed becoming popular. These plants consist of integrated and sequential treatment lines, which allow to recovery of renewable energy in the form of biogas stabilise the biomasses, and, with the subsequent aerobic treatment (i.e., composting), transform the digestate into a soil improver for its use in agriculture. Table 3 reports the advantages and disadvantages of the AD process.

3.2.1. Anaerobic digestion plants in Italy

According to the most recent census, in 2010 Italy had a total of 672 biogas plants, of which 273 operated using livestock effluents, energy crops, and agricultural and food waste (AFW). Additionally, 14 plants processed organic fraction of municipal solid waste (OFMSW), sometimes in co-digestion with sewage sludge, while 32 plants were dedicated exclusively to treating wastewater from the agro-industrial sector (Table 2). The greatest density of plants is in the Po Valley, where most of the Italian livestock production is also present. Together, the regions of Lombardy, Emilia-Romagna, and Veneto generate more than 60 % of Italy's biogas output [42]. Of the 273 biogas plants operating in the agro-livestock sector, approximately 33 %, equal to 91 plants, used only livestock effluents, while 51 % (139 plants) co-digested livestock effluents with energy crops and AFW. AD plants in Italy employ different reactor configurations, primarily completely stirred tank reactors (CSTRs) and plug flow reactors (PFRs), to optimize biogas production based on feedstock properties. CSTRs, which were used by 155 of the agro-livestock sector plants, allow thorough mixing of feedstocks, essential for consistent gas production from high-moisture AFW and livestock effluents. PFRs, used in 63 plants, are more suitable for feedstocks with higher solids content, as they allow the substrate to move continuously through the reactor, reducing the chance of material accumulation.

Most Italian AD plants operate under mesophilic conditions (~37°C), which are energetically favorable for AFW. In the warmer Southern regions, however, some facilities utilize thermophilic conditions (~55°C), which can enhance the degradation rate of more resilient substrates, though they require greater energy input.

Co-digestion strategies differ by region: Northern Italy, with abundant livestock farms, primarily digests livestock manure with energy crops like corn, sorghum, and triticale. Southern regions, where livestock farming is less intensive and climate conditions are less suitable for corn, utilize alternative co-substrates, such as pomace, olive mill wastewater, and citrus residues. The use of regionally available crops like sulla (*Hedysarum coronarium*) is explored to substitute corn silage, addressing both local availability and sustainability concerns [44].

As of 2019, Italy ranked third worldwide for medium- and large-scale AD facilities, following Germany and China, with over 1500 plants [45]. AFW, due to its high agricultural production in Italy, offers an abundant and underutilized resource for AD, with methane yields that can surpass those of traditional energy crops (e.g., carrot leaves, potatoes, onion peels). Typical biogas yields ($m^3/ton_{fresh\ matter}$) for Italian AFW are 108 for sunflowers, 40 for eggplants, 76 for pumpkins, 57 for cauliflowers, 56 for cabbage, 36 for sweet peppers, 32 for tomatoes, 28 for cucumbers, and 172 for potatoes by-products [46]. However, the seasonal availability and high moisture content of many AFWs create storage challenges, often leading to rapid spoilage. Moreover, crop residues, mowing, and straw can result in floating layers within the mass under digestion that are difficult to remove and require pretreatment [47]. Additionally, lignocellulosic biomass, a valuable feedstock for AD, poses technical difficulties due to cellulose crystallinity and lignin content, which hinder enzymatic hydrolysis. This substrate typically requires physical or chemical pre-treatment to enhance biodegradability [48].

The most representative region in terms of number of plants treating livestock effluents and/or AFW and/or energy crops is still Lombardy, accounting for 21 % of the national total. Interestingly, Chinnici et al. in 2018 presented an assessment of the potential energy supply and biomethane production from the AD of AFW in Sicily and estimated an annual average of 232,567 tons of biomass over 2013/2014, of which 35,917 tons are whey, 42,277 tons are pomace, grape stalks, and dregs, 20,479 tons are olive residue, and 4379 tons are waste from slaughtering [44].

3.3. Combustion

Combustion is an exothermic reaction between fuel (biomass) and oxygen (air) to produce mainly carbon dioxide, water, and heat. Direct combustion represents around 97 % of biomass applications in energy production over the world [49]. The heat released can be used to produce electricity by the Rankine cycle (by using water or an organic fluid) in combined heat and power plants (CHP) [50]. While some authors regard combustion not as a valorization process per se—since it does not isolate valuable compounds but instead focuses on energy production—it is included in this review as it transforms agricultural residues into a usable form of energy, contributing to the easily accessible management of these resources, since combustion and combustion plants are consolidated both as process and technologies in the Italian context. The main advantages and disadvantages of direct combustion processes are reported in Table 3.

Combustion is a mature process with TRL 9. A wide range of biomass waste can be used, such as wood materials (e.g. sawdust, wood chips, wood logs, bark paper), AFW (e.g. wheat straw, rice straw, corn husks), municipal/industrial wastes, and dedicated energy crop (e.g. switchgrass). Direct combustion is always technically viable for AFW, but it is convenient only if an adequate process is chosen and if some biomass properties are correctly evaluated. The key parameters to consider are moisture, ash content, and chemical composition [49]. Although large-scale combustion plants can efficiently manage high ash content biomass (<50 % grate fire, <10 % fluidized bed), the presence of high alkali contents and low melting point ashes implicates bed agglomeration and slagging/fouling issues. Since water negatively affects heat produced by combustion, biomass with a moisture content of less than

Table 2
Number of plants, location, and typology of feedstocks used in biogas plants surveyed in Italy in March 2010 by the CRPA (Animal Production Research Center) census [43].

	Livestock effluents and/or AFW and/or energy crops	OFMSW	Process and washing wastewater from agro-industrial plants	Civil sewage sludge	Biogas from municipal waste landfill	Total
North	244	12	22	81	124	483
Center	13	1	3	24	48	89
South	16	1	7	16	60	100
Total	273	14	32	121	232	672

AFW, agro-food waste; OFMSW, organic fraction of municipal solid waste.

Table 3
Advantages and disadvantages of industrial-scale processes treating AFW.

	Advantages	Disadvantages
Composting	AFW composting represents a closed-loop system to recycle nutrients and soil fertility by reducing the use of chemical fertilisers	The composting facilities require space
	Composting reduces GHG emissions compared to other AFW treatments	The quality of compost depends on the type and amount of AFW and operational conditions
	The use of compost contributes to attaining a more sustainable and eco-friendly farming approach and reduces the disposal costs of AFW	If not properly managed and designed, composting may not reach the conditions needed for complete stabilization and it may lead to the spread of pathogens
Anaerobic digestion (AD)	Biogas is an environmental and cost-effective energy resource compared to others produced through biochemical processes	Constant monitoring of key parameters such as pH, temperature, feed rate, microbial culture stabilisation, and production of inhibitors is required
	AD produces a lower amount of final sludge and odours compared to aerobic processes	Feedstock is required to be collected, transported, and pretreated (especially the lignocellulosic one) before AD
	The final residue (i.e., digestate) after AD is rich in nutrients and can be used in agriculture as fertilizer	Post-treatment of the waste generated by the process before discharge to the environment can be necessary
Combustion	In combustion processes a wide range of AFW with high moisture (< 60 %) and ash contents (< 50 %) can be used	High investment and operating costs, such as for the correct disposal of ashes
	Electricity from biomass plants provides a consistent load, which enables more precise regulation of power grid frequency, unlike wind and solar power technologies	To mitigate combustion emissions from biomass firing and meet government legislation, additional systems must be implemented
	The release of GHG emissions is lower than the ones derived from energy based on petroleum source	High-alkali biomass with low melting points can cause bed agglomeration, and slagging on furnace walls and superheater tubes

AD, anaerobic digestion, AFW, agro-food waste; GHG, greenhouse gases.

60 % should be fed in power plants [51].

There are three main configurations for biomass combustion on a large-scale size plant: grate firing, fluidised bed, and pulverised bed. The grate fire plant pushes the biomass through the furnace by using a moving grate, offering a high fuel versatility since it allows the use of coarse (<300–400 mm) and uneven particles, and it is not affected by impurities (e.g. stone, metal) making it the main choice for burning of difficult and inhomogeneous substrates as municipal wastes [50]. On the other hand, low combustion efficiency and high pollutant emissions are the major drawbacks due to scarce fuel-to-air mixing, low heat transfer, and high temperature (1200–1400 °C) [52]. Fluidised bed technology mixes fuel particles with an inert medium, facilitating excellent mixing and efficient heat transfer at lower combustion temperatures. This configuration releases low thermal NO_x emission due to the low combustion temperature [52]and a reduced SO_x content by injecting limestone into the furnace [52], but it promotes a high erosion rate of boiler surfaces in contact with the bed material and a high energy consumption request and bed agglomeration [52]. In pulverised-fuel combustion, the fuel is ground (<100 mm) then mixed with heated combustion air and pneumatically injected in a burner to obtain a burnout of suspended particles which occurs fast (1–2 s) and at high temperatures (1300–1700 °C) [50]. The comminution step of biomass is the critical point for direct co-firing application because feedstocks must be made similar to coal (moisture <20 %, particle size <2 mm) [52]. If biomass is ground with coal (co-milling), the feedstocks exploitable are limited to sawdust and wood pellet, while the use of dedicated mills increases the biomass share and expands the range of available fuels (e.g., pre-dried wood chip) [52].

3.3.1. *Combustion plants in Italy*

Although the number of combustion plants in Italy has decreased in recent years, the amount of waste disposed in these plants is stable, primarily due to efficiency improvements in existing facilities. Statistics in this sector are not always homogeneous and often approximate. However, data from ENAMA (National Board for Agricultural Mechanization) [53], FIPER (Federation of Italian Producers of Renewable Energy) [54,55] have been retrieved, as well as direct contacts with some of the power plant companies. The requested information included boiler thermal power, electric power, and annual biomass consumption. Additional information, only for some power plant companies, was retrieved through direct contact regarding the type of biomass boiler and the types of solid biomass used. The results of the analyses have been divided by small and medium power, mainly district heating and small cogeneration plants, and high-power plants (CHP) mainly used for electric production. Regarding small to medium-sized plants, there are over 200 district heating plants. Some of these plants recover heat for industrial use (e.g. to power the dryer of pellet production plants). In Italy, the overall thermal power installed is about 652 MWth, and an annual consumption of 97913 GWht is estimated. This evaluation takes into account the relationship between installed power and energy produced and the plant efficiency by 90 %. Overall, almost half of the plants have a thermal power below 1 MWth, while just 6 % of the plants exceed 12 MWth. The vast majority of the plants are fuelled by residual wood chips from forestry operations or residues from sawmills.

Regarding high-power plants, there are approximately 30 plants with a power exceeding 3 MWe, mostly located in Northern regions. The type of biomass consumed is highly variable and includes not only woody forest residues but also agricultural residual feedstocks. In Italy, chopped wood and, to a lesser degree, rice husk, and olive wastes are the most often burned biomasses in power plants [56]. In general, wood pruning, wood from uprooted trees, olive pomace and grape marc, maize stalks and straw, and various types of nutshells are often used. From a legislative point of view, the solid biomasses that can be used for direct combustion in large-scale plants are regulated by the Italian Consolidated Law on the Environment [57]. In particular, the annual biomass consumption for these types of plants exceeds 4.5 million tons, with an average calorific value of about 10.5 MJ/kg.

The region with the highest number of incinerators is Lombardy. Of the million tons of waste incinerated in a year, 72 % is burned by plants in the North, 18 % in those in the South, and nearly 10 % in those in the Center. The largest combustion plants in Italy are in Acerra (Southern Italy) and Brescia (Northern Italy). The Brescia plant is owned and operated by A2A S.p.A. company and is capable of processing more than 500,000 tons of waste on three independent combustion lines from which enough heat is generated to heat more than 30,000 homes connected to the district heating network [58]. The most advanced processes have been adopted in the plant to ensure the lowest environmental impact on atmospheric emissions, noise, liquid discharges, and solid residues. Flue gas treatment complies with the most stringent national and European regulations, ensuring optimal levels of pollutant abatement. Emissions are monitored 24 hours a day by sophisticated systems. Data are displayed not only on company websites but also on the display located outside the plant. The AFW most used by the plant are wastes from the preparation and processing of meat, fish, and other foods of animal origin and wastes from the preparation and processing of fruits, vegetables, cereals, edible oils, cocoa, coffee, tea, and tobacco, and from the production of canned food. Another virtuous example in Italy is the Castiraga Vidardo plant (Northern Italy). The feedstocks fed to the plant are combustible solid biomasses derived from green and forestry management activities, wood and wood by-products processing activities, from agricultural, agro-industrial, and food activities of cereals, legumes, rice, olives, hay, straw, nuts, corn. Combustible wastes are obtained from a refining processing cycle that includes shredding, drying, stabilization of the organic fraction, separation of metals, and removal of aggregates; thus, a non-hazardous fuel with good energy content and consistent chemical-physical characteristics meeting specific technical standards is obtained.

4. Pilot-scale processes

Thermochemical (e.g., pyrolysis, gasification) and biological (e.g., fermentation) processes for biofuel and bioplastic generation from organic waste are studied from research to industrial scales. This paragraph discusses the advantages and disadvantages of scaling up these processes to industrial levels, tailored to the characteristics of the organic waste and desired end products. A geographic overview of pilot and industrial plants is provided (Fig. 3(a)). Among thermochemical processes, combustion is commercially used for biomass management, while pyrolysis and gasification are still in development. The main challenge in scaling up thermochemical processes is the cost and process complexity. Fermentative processes are primarily at laboratory and pilot scales due to the significant capital investment required for upscaling. Most of the information reported about thermochemical and biochemical pilot plants was based on interviews conducted with the plant operators.

4.1. Pyrolysis

Pyrolysis is a thermal degradation process performed between 300 and 800 °C under an inert atmosphere. The three main products of pyrolysis are biochar (the solid phase), bio-oil (the liquid phase), and pyrogas (the gas phase) [59]. According to a circular economy vision, pyrolysis could be considered an integrated process able to produce both renewable energy and materials for different applications. The pyrolysis process is divided into three main categories according to the heating rate and residence time: slow, intermediate, and fast pyrolysis [60]. Slow pyrolysis requires a slow heating rate (less than 10 °C/min) and a long residence time (between hours and days), and the main product is biochar. Fast pyrolysis entails a fast-heating rate (higher than 100 °C/s) and a short residence time (less than 2 °C/s) with rapid quenching of the volatiles leading to the main product as bio-oil, and the biochar as co-product [61]. The quality of the product(s) depends on the chemical and physical properties of the feedstocks. In particular, the pyrolysis process requires feedstocks with limited moisture content (<15 $\%_{w/w}$) which is usually reduced through thermal pretreatments, such as drying and torrefaction [62]. However, these pretreatments consume a significant amount of energy; consequently, optimisation of the pretreatments and pyrolysis equipment would reduce the overall energy demand of the entire process which consequently slows down the industrial development of the process. Other adopted pretreatments for the pyrolysis process include the addition of catalysts and the performance of microwave assistance [63].

Currently, the studies concerning the pyrolysis of AFW focus on the improvement of the characteristics of the chosen feedstocks through the control of the pyrolysis temperature, residence time, addition of catalyst, and physical and chemical activation of the feedstocks and products [64]. These parameters are widely studied since appropriate process conditions can reduce secondary reactions in pyrolysis and improve the biochar, bio-oil, and pyrogas yields. Among all the process parameters, temperature is the most important factor influencing the distribution and quality of products [65]. A higher pyrolysis temperature promotes secondary reactions that could reduce biochar, pyrogas, and bio-oil yields by requiring more energy consumption, whereas a lower pyrolysis temperature can lead to incomplete devolatilization [66]. The main advantages and disadvantages of pyrolysis are scrutinised in Table 6.

According to bioeconomy pillars, the pyrolysis of AFW could represent an integrated biorefinery, since all the products (biochar, bio-oil, and pyrogas) can be considered carriers for renewable energy productions and materials for different applications. However, the quality of these products depends also on the scale and type of reactor. Currently, the pyrolysis is mostly performed in batches at the laboratory scale with volume ranging from 0.025 L to 1 L [67] and at the pilot scale in continuous feed from 5 to 120 kg/h as proven in Table 4.

The biochar derived from AFW is an effective material for carbon

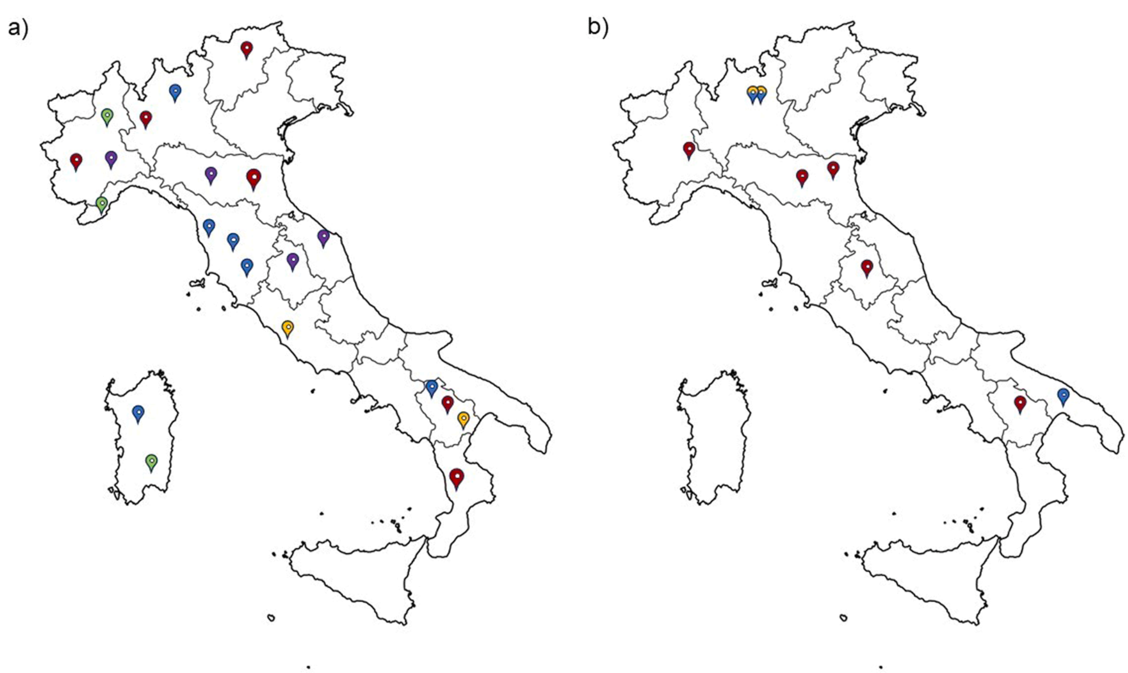

Fig. 3. (a) Operating pilot-scale pyrolysis (blue), gasification (red), sequential pyro-gasification (yellow), fermentative (green), and bioplastic-producing (violet) plants in Italy in 2024 treating agro-food waste. (b) Operating plants with bacteria (blue), fungi (yellow), and insects (red) in Italy in 2024.

Table 4
Available plants performing pyrolysis processes in Italy, by considering their geographical position, technological readiness level (TRL), type of reactors, daily capacity, and main products obtained.

Region	TRL	Technology	Type of reactor	Waste	Capacity	Products
Lombardy (North)	9	Pyrolysis	Fixed bed reactor (500–600°C)	AFW, urban waste	1200 kg/h	Energy and (bio)char
Tuscany (Center)	3	Pyrolysis	Continuous oxidative carbonization unit	AFW (semi-dry)	40–50 kg/h	Biochar,bio-oil, and pyrogas
	4	Pyrolysis	Carbonization unit		100 kg/h	Biochar, bio-oil, and pyrogas
	2	Pyrolysis	Two slow to intermediate pyrolysis units		1–3 kg/h and 4–6 kg/h	Biochar, bio-oil, and pyrogas
Lazio (Center)	2	Sequential pyro-gasification	Pyrolysis with a drum reactor, and gasification in a fluidised bed reactor	Urban waste	Pyrolysis feed: 5–50 g/min; Gasification feed: 1–30 g/min	Syngas with high hydrogen and carbon content (for fuel application)
Basilicata (South)	4	Pyrolysis	Fixed bed reactor (500–600°C)	Residues of carbon fiber composites reinforced with epoxy resins	10 kg/h	Recovery of carbon fiber
	4	Sequential pyro-gasification	Rotative drum reactors	AFW, waste tires, and animal fluff	30 kg/h	Syngas with high hydrogen content
Sardinia (South)	9	Pyrolysis	Auger reactor	AFW, tires, unseparated urban waste	1250 kg/h	Energy

AFW, agro-food waste.

sequestration to mitigate climate change, for the adsorption of pollutants, and for catalyst support [64]. Specifically, biochar is recognized as a long-term carbon storage [65], a good energy carrier with a high heating value of 12–30 MJ/kg, representing a promising potential solid fuel. Furthermore, biochars derived from AFW, like eggshells, animal bones, and soybean dregs biochar can replace active carbon because their pore structures promote ion movement and offer opportunities for doping with heteroatoms like nitrogen, oxygen, phosphorus, and sulfur, enhancing their performance in energy applications [68].

Bio-oil, the main product of fast pyrolysis up to 600–700 °C, is considered an economic and environmentally friendly fuel, and it is one of the most promising candidates to replace traditional fossil fuels [69]. Bio-oil has some advantages such as less toxicity, better biodegradability, and lower sulphur-nitrogen contents in comparison to fossil fuels. However, the current limits in the application of bio-oil for the replacement of fossil fuels, are 1) the presence of a mix of valuable compounds in low amounts which makes the upgrade difficult and expensive, and 2) the water content, which decreases its density and increases its gross calorific value. The catalytic pyrolysis of AFW is an efficient method for enhancing the production of bio-oils for use as liquid fuels. Hydrogen, recognized as a clean future fuel, can be derived from biomass pyrolysis. A study using maize stalks' bio-oil as feedstock demonstrated that the hydrogen yield increased with temperature and water-to-carbon molar ratio and the highest hydrogen yield reached 71.4 % at 900 °C [70]. Renewable biochemical compounds can be obtained by the treatment of the bio-oil, specifically phenolic molecules and levoglucosenone. Phenol is the simplest phenolic compound, that can be used as the feedstock for different products like fungicides, drugs, and resin. However, the content of phenolic chemicals in the bio-oil is low due to poor pyrolysis selectivity and limited lignin content. As an example, Li et al. in 2020 [71] tested fast pyrolysis with an activated carbon catalyst and successfully produced levoglucosenone from cellulosic biomasses (pine wood, bagasse, and poplar wood) [67].

4.1.1. Pyrolysis plants in Italy

The main pilot plants identified in Italy are five and they are located one in the North, two in the Center, and two in the South of Italy. The main available features, such as the type of reactor, mass flow rate, and biomasses treated by the detected pyrolysis pilot plants are reported in Table 4.

The plants in Tuscany and Basilicata include multiple reactors with different configurations (fixed bed, continuous, etc.) and sizes offering the possibility to perform a wide range of tests at a pilot scale. The pilot plants outlined in Table 4 are employed for validating and scaling up pyrolysis processes explored at the laboratory scale, which were carried out within the framework of regional, national, and EU projects. Most of the available pilot plants can treat AFW, without any specific indication of their qualitative composition, but the biomasses are required to have a water content lower than 50 $\%_{w/w}$. Some of the identified plants, like the ones in Basilicata and Sardinia, can treat AFW and inorganic feedstock like carbon composite and tires demonstrating that pyrolysis could be a versatile process.

No specific information is available for the five pilot plants identified, except for the three ones available in Tuscany. In detail, the first pilot plant is a continuous oxidative carbonization system treating 40–50 kg/h of feedstock. It is made of stainless steel and comprises three main sections: biomass loading and conversion, charcoal discharge and cooling, and pyrolysis vapor extraction and combustion.The second pilot plant is a rotating kiln including an externally heated rotating pyrolysis reactor, a refractory-lined combustion chamber for pyrolysis vapor post-combustion, and a gas-to-water heat exchanger with a dry-cooler. This plant can convert 100 kg/h of biomass into biochar and heat, with natural gas for startup. The third plant is an auger reactor, which processes up to 3 kg/h of biomass at up to 600 °C. Biomass enters through an air-tight double gate-valve system, with adjustable reactor screw speed for varied residence times. It has an auxiliary gas port for injecting inert or oxidant gases to study oxidative or inert pyrolysis. Three independent heating sections offer precise temperature control and flexibility.

The pyrolysis plant located in Sardinia employs a pyrolytic process to convert organic waste into clean fuel gases for industrial use. The energy demand of the plant is balanced by the produced gas, while the excess gas is utilized for electricity production. The quality of the fuel ensures the quality of emissions since clean gas combustion corresponds to clean emissions.

The lack of specific information for the other identified pilot plants proves the necessity for deeper communication and information about them to use them to validate laboratory scale processes about different types of biomasses and other feedstocks.

Despite its potential, the widespread adoption of pyrolysis has been limited by challenges related to scaling up operations, integrating with existing waste management infrastructure, and securing markets for the produced materials. However, it is worth mentioning, that pyrolysis plants are mainly located in the Center and Southern of Italy, whereas combustion plants are mainly geolocalised in the Northern of Italy. The presence of pyrolysis plants in that part of the Italian territory is due to the availability of space and the presence of a big research centre equipped with these reactors.

Overall, pyrolysis is promising for waste conversion and energy generation as proven by laboratory tests. At the laboratory scale, both slow and fast pyrolysis have been adopted as a promising treatment for lignocellulosic agro-residues like rice husk, crop residues, miscanthus, and switchgrass. Specifically, lignocellulosic, rice husk and crop residue are two AFWs ideal for slow and fast pyrolysis due to their availability, low nitrogen content, and stable properties. In slow pyrolysis, biochar production from rice husk is performed at 400–550 °C with a 5–15 °C/min heating rate, and 30–120 min residence time, while biochar from crop residues occurs at 350–550 °C with similar conditions [72]. In fast pyrolysis, the bio-oil production of rice husk and crop residue is done at 420–540 °C and 400–700 °C and it is suitable for various applications [67].

The abovementioned feedstocks have been investigated in the EU project carried out by the Tuscan plant (i.e., BABILOC, Re-JET) concerning both slow and fast pyrolysis processes.

4.2. Gasification

Gasification is the conversion of solid or liquid feedstocks into a gaseous fuel that can be burned to release energy or used to produce value-added chemicals in the presence of oxidizing agents such as oxygen, air, or vapor. The main target of the gasification process is syngas, which is a gas mixture mainly formed by H_2 and CO, extremely used both as it is and as a platform chemical [73].

Gasification and combustion differ in three main aspects [74]. Firstly, gasification forms chemical bonds in the product gas, while combustion breaks them for energy release. Secondly, gasification boosts the hydrogen-to-carbon ratio by adding hydrogen, whereas combustion oxidises both hydrogen and carbon. Lastly, gasification operates with fewer oxidising agents to regulate the reaction, while combustion uses a stoichiometric amount for optimal fuel oxidation. A typical gasification process involves preheating, drying, pyrolysis, partial combustion, and gasification steps [74] often overlapping without clear boundaries.

In commercial gasifiers, the thermal energy necessary to dry, perform the pyrolysis and support the endothermic reactions comes from a certain amount of exothermic combustion reactions occurring in the gasifier [75]. For each kilogram of moisture removed from the biomass, a minimum of 2242 kJ of extra energy from the gasifier to vaporize water is required, with this energy being not recoverable [76]. Hence, feedstocks with a high level of moisture can represent a limit due to the energy necessity and economic cost. The typical moisture content of freshly cut woods and lignocellulosic biomass ranges between 30 % and 60 % $_{w/w}$. To produce a fuel gas with a reasonably high heating value, most gasification systems use dry biomass with a moisture content between 10 % and 20 % $_{w/w}$ [74].

The most important operational parameters in the gasification processes are the oxidizing medium and the reactor configuration. For gasification, the main gasifying agents employed are oxygen, steam, and air. The employment of a medium is essential for the gasification process, whereas it is not required for pyrolysis and torrefaction. It is important to underline that in a gasifier the heating value and the composition of the produced gas are strong depending on the nature and amount of the gasifying agent employed [74]. The design and operation of a gasifier require knowing the gasification process, the configuration, the size, the composition of the feedstock, particle size [77], and other operating parameters that influence the performance of the plant.

Despite its potential benefits, the gasification of AFW faces three main challenges. The first is the variability in feedstock composition and availability, which can affect gasifier performance and syngas quality. The second concern is the high capital costs and technical complexities associated with gasifier design and operation. The last one is the management of ash and tar produced during gasification, which can require additional processing and disposal processes [73]. The advantages and disadvantages of the gasification process are described in Table 6.

All these challenges are under investigation at the laboratory and pilot scale. In detail, the literature reviews and case studies performed at laboratory and pilot scale provide valuable insights into the gasification of AFW, by addressing different aspects such as technological advancements, performance evaluation, and feedstocks. However, tar content in syngas from biomass typically exceeds acceptable levels for downstream use. Catalysts, such as Ni-based catalysts, dolomite, and olivine, can enhance syngas yield from biomasses by catalytically converting condensable fractions, thereby reducing tar content, and improving downstream [78].

Another important application of syngas is the fermentation of syngas. In detail, syngas fermentation is used industrially to produce diluted bioethanol (1–6 wt%) [79]. Syngas fermentation is a process where anaerobic microorganisms convert syngas into compounds such as ethanol, acetate, butanol, and other biofuels or chemicals [80]. Syngas fermentation has gained attention as a promising process for sustainable biofuel and biochemical production due to several advantages. However, challenges such as low conversion efficiency, product toxicity, and the need for robust microorganisms and efficient bioreactor designs still need to be addressed for the widespread commercialization of syngas fermentation processes [81].

4.2.1. Gasification plants in Italy

The available gasification plants in Italy are in total six and they are located two in the North, two in the Center, and two in the South of Italy. The main available features, such as the type of reactor, mass flow rate, and biomasses treated by the identified gasifier pilot plants are reported in Table 5.(Table 6)

Currently, gasification in Italy has been adopted as a promising treatment for plastic waste and unseparated urban waste. However, gasification could be a key process for small-scale farmers who often rely on fossil fuel-based products and inefficient biomass practices for heating greenhouses and fertilizing crops, contributing to air and water pollution. Most of the available studies concern the gasification of lignocellulosic matter, a widely available residue in Italy. Among them, fixed bed gasification is a favourable method for treating lignocellulosic material due to its suitability for small-scale operations (<1 MWth) and its simple and robust process [82]. This makes it possible for integration into smart energy networks or use by isolated small communities. Most of available AFW are characterised by low bulk density and tar production. Recent advancements in feeding low bulk density biomass, tar reduction, and tar reforming have increased the applicability of a wider range of AFW and achieved higher syngas conversion rates, as proved by the study of Cerone at al,2018 [83] about nutshells. Nutshell is a residue of interest for small-scale gasification due to its abundance from agro-industries located in Piedmont (Northern Italy). Gasification of nutshells in downdraft mode has produced syngas with high calorific value without bed bridging or ash fusion [83].

Another investigated biomass is wood. In South Tyrol (Northern Italy) there are multiple gasifiers are working with 22500 tons of wood biomass to produce 42 GWhel and 1300 tons of char, currently treated as waste, but there is significant interest in exploring alternative methods for utilizing such solid by-products [84]. In Lazio (Central Italy), there is a small steam gasification fluidized bed reactor (250 KWh) that converts AFW coming from viticulture (2–6 tons per year) into energy, constantly investigating the biomass availability and energy consumption to design a more energy sustainable process [85].

No further specific information is available for the six pilot plants identified, except for the ones available in Calabria. In detail, this system is an up-draft fixed-bed reactor, air-fed and designed to operate at near-atmospheric pressure, capable of gasifying various types of coal and biomass. It has been tested for both woody biomass gasification and coal-biomass co-gasification. The gasifier, with an internal diameter of 1300 mm and a height of 2800 mm, can support a fuel bed up to 2400 mm. Fuel is loaded from a top hopper through a Y-shaped conduit equipped with three guillotine gates for precise timing control.The

Table 5
Available plants performing gasification processes in Italy, considering their geographical position, technological readiness level (TRL), type of reactors, daily capacity, and main products obtained.

Location	TRL	Technology	Type of reactor	Waste	Capacity	Products
Piedmont (North)	3–4	Gasification	Fixed bed	Unseparated waste, plastics	5 kg/h, 50 kg/h, 250 kg/h.	Pyrogas, hydrogen (>40 %), and energy
Lombardy (North)	5	Gasification	Fixed bed	AFW, waste tires, unseparated urban waste	400 kg/h	Energy
Trentino South Tyrol (North)	4	Gasification	Fluidised bed	Woody biomass	225000 m^3/y	42 GWhel, 200 tons of char
Emilia Romagna (North)	4	Gasification	Fixed bed	Unseparated waste, plastics from the sea	100 kg/d	Pyrogas, hydrogen (>40 %), and energy
Lazio (Center)	2	Sequential pyro-gasification	Pyrolysis with a drum reactor, and gasification in a fluidised bed reactor	Urban waste	Pyrolysis feed: 5–50 g/min; Gasification feed: 1–30 g/min	Syngas with high carbon and hydrogen content (for fuel application)
Basilicata (South)	4	Gasification	Fluidised bed	Secondary solid fuels	10 kg/h	Syngas with high hydrogen content
	4	Sequential pyro-gasification	Rotative drum	AFW, waste tires and fluff	30 kg/h	Syngas with high hydrogen content
Calabria (South)	7	Gasification	Fixed bed	Exhausted pomace	1000 kg/h	Energy

AFW, agro-food waste.

system includes a gasification section, a co-current scrubber for syngas cleaning, and a flare. The scrubber uses three conical nozzles to wash the syngas with water, also acting as a hydraulic flashback guard. A demister with eight perforated disks removes residual water, while separated tar collects at the scrubber's base and is extracted by a single-screw pump.

As noted in paragraph 4.1.1 about pyrolysis plants, addressing data gaps on other pilot plants is crucial to enable their use in testing, validating, and scaling lab-scale both pyrolysis and gasification. Detailed specifications could confirm if these facilities address experimental requirements, by supporting reliable validation and effective scaling from lab to pilot scale and consequently allowing the implementation at the industrial scale.

4.3. Fermentation for biofuel production

Microorganisms like bacteria or yeast can convert organic substrates into biofuels via fermentative processes. AD is an established and mature industrial process for bioenergy production, whereas other fermentative processes, explored at laboratory and pilot scales, focus on producing biofuels such as butanol, hydrogen, and ethanol. Fermentative processes, especially for AFW, often require pretreatment(s) to break down complex structures and improve cellulose and hemicellulose accessibility. Enzymes like cellulases and amylases can break down complex carbohydrates into fermentable sugars, crucial for obtaining sugars from the feedstock [86].

Biobutanol production from AFW typically involves the utilisation of lignocellulosic biomass (e.g., corn stover, wheat straw, rice straw), and its main steps are substrate preparation, hydrolysis, fermentation, and distillation [87]. Hydrolysis could be performed with enzymes such as cellulases and hemicellulases or with alkali, acid, or steam explosions. The hydrolysed sugars are then fermented by microorganisms capable of producing biobutanol, like *Clostridium acetobutylicum*. At the end of fermentation, the fermentative broth contains a mixture of butanol, along with acetone and ethanol. Several separation and purification techniques are employed to recover biobutanol from the fermentation broth, with distillation being often used to obtain a higher concentration of biobutanol. Scientific studies performed at the laboratory scales reported that physically pretreated cereal biomasses like corn stove [88] and straw [89] lead to a biobutanol yield range between 6 and 10 g/L, respectively, while for sugar biomasses like cassava bagasse, its hydrolysate led to a yield of 15 g/L [90]. The remaining solid residue after enzymatic hydrolysis (mainly lignin), can be used for various purposes, such as bioenergy production or as a source of chemicals. Challenges in biobutanol production from AFW include the complexity of lignocellulosic biomasses, the need for efficient pretreatment methods, and the optimization of fermentation conditions. Advances in biotechnology and process engineering are continuously being explored to enhance the economic viability and sustainability of this approach [91]. Biobutanol is getting interested in its capability to be a renewable replacement for gasoline since it could be used as a fuel in vehicles without modifying the engine system [91].

Dark fermentation, consisting of the first two steps of AD (hydrolysis and acidogenic), involves the anaerobic breakdown of organic substrates by microorganisms, leading to the production of hydrogen gas, carbon dioxide, and organic acids. Microbial metabolism typically proceeds through a series of enzymatic reactions, resulting in the conversion of sugars or other organic compounds into microbial biomass and hydrogen as the main high-added value compound. Dark fermentation has gained attention as a potential method for bio-hydrogen production, and it can treat various organic feedstocks, including sugars, starch-rich, cellulose-rich substrates, and other biodegradable organic materials [92]. The main exploited microorganisms belong to the *Clostridium* genus, such as *Clostridium acetobutylicum* and *Clostridium butyricum*, which are known for their ability to produce hydrogen as a metabolic by-product. Several factors influence the efficiency of dark fermentation, including temperature, pH, substrate concentration, and the type of microorganism used [92]. After dark fermentation, the produced hydrogen needs to be recovered from the fermentation broth. Different methods, such as gas stripping or membrane separation, can be employed for efficient hydrogen recovery. Scientific studies performed at the laboratory scales reported that from vinasse the H_2 yield range between 150 and 253 g/L [93], and from palm oil waste the yield is 135–142 g/L [94]. Dark fermentation not only produces hydrogen but also results in the formation of organic acids. These organic acids can be valuable as chemical precursors or as by-products that can be further utilized, like fatty acids. Dark fermentation has the advantage of being relatively simple and can operate on a variety of feedstocks, including waste materials. However, challenges such as low hydrogen yields, the presence of by-products, and the need for further optimization to enhance efficiency still exist. Ongoing research focuses on improving the performance of dark fermentation for sustainable hydrogen production and exploring its integration with other processes for a more comprehensive approach to biohydrogen production. Both for biobutanol and biohydrogen production, the process conditions are optimized to maximize the energy production and minimize the formation of by-products.

Bioethanol production involves the conversion of biomass into ethanol through fermentation. This process is commonly used as a renewable alternative to fossil fuels and chemical production. Common

Table 6
Advantages and disadvantages of pilot-scale processes including pyrolysis, gasification, bioplastic production, and fermentation.

	Advantages	Disadvantages
Pyrolysis	Pyrolysis of AFW improves waste management, and resource recovery, and mitigates environmental pollution	Pyrolysis requires high energy inputs which reduce the overall energy efficiency of the process and increase the operational costs
	Pyrolysis produces energy-rich products that contribute to energy diversification and the reduction of reliance on fossil fuels	Implementing pyrolysis systems requires complex equipment and expertise, which can be expensive to establish and maintain
	Biochar is a stable form of carbon-rich material	The composition and quality of the products depend on feedstock type, pyrolysis conditions, and process parameters.
Gasification	Syngas is a versatile fuel and intermediate product, which represents an alternative to fossil-based compounds	Syngas produced from AFW gasification typically contain impurities
	AFW gasification can offset CO_2 emissions during combustion	Integrating AFW gasification systems into existing infrastructure can be challenging because of the high capital and maintenance costs
	AFW gasification can utilize a variety of feedstock by reducing the amount of solid waste to dispose	The supply of a constant amount of feedstock can be challenging
Bioplastic production	Bioplastics produced through the utilization of AFW reduce the dependence on finite resources and improve waste management	Bioplastic downstream is more energy-consuming compared to the traditional plastic one
	Bioplastics could be biodegradable, compostable, or both and allow lower amounts of GHG emission than petrochemical-based plastics	Many bioplastics are marketed as biodegradable, but their degradation rates and environmental impacts can vary depending on temperature, moisture, and microbial activity
	Bioplastics can be tailored to obtain a wide range of properties, making them suitable for various applications	Bioplastic production is currently limited in TRL compared to petrochemical-based plastics since the cost of scaling up processes remains a challenge
Fermentation	Biofuels from AFW are renewable fuels able to improve AFW management	The availability and transportation cost of feedstock can affect the economic viability of biofuel production
	Biofuels produce fewer GHG emissions when burned, compared to traditional fossil fuels	Biofuel production has a TRL limitation due to the necessity of reducing production costs and scaling up production to meet the demand
	Biofuel production processes can capture and utilise CO_2 by reducing GHG emissions	Downstream of the products requires expertise and economic investment

* AFW, agro-food waste.

feedstocks include sugarcane, corn, wheat, and other biomass resources rich in sugars or starch [95]. Lignocellulosic materials, such as agricultural residues and forestry waste, can be used as feedstocks in second-generation bioethanol production [86]. The hydrolysed sugars are fermented, typically using yeast species such as *Saccharomyces cerevisiae*. The fermentation process is carried out under anaerobic conditions to ensure efficient ethanol production. After fermentation, distillation is employed to separate ethanol from the fermentation broth, concentrating the ethanol to the desired purity. An optional step is dehydration, which may be applied to remove any remaining water from the ethanol, further increasing its purity. Common methods include molecular sieves or azeotropic distillation. After the dehydration, another optional step can be performed, i.e., denaturation, to make the ethanol unsuitable for consumption and suitable for industrial applications or fuel use. Various additives, such as corrosion inhibitors or stabilizers, may also be introduced depending on the intended application. Based on scientific studies, lignocellulosic biomass exhibited the highest bioethanol yield ranging between 450 and 510 L/t [96] starch-based biomass around 365–535 L/t, and sugar-based biomass around 70–107 L/t [97]. The residues from bioethanol production, such as leftover biomass or spent yeast, can be used for other purposes, such as animal feed or as a source of additional energy. Bioethanol production is a well-established process, and ongoing research aims to improve efficiency, reduce costs, and explore advanced feedstocks to make bioethanol a more sustainable and economically viable alternative to conventional fossil fuels.

4.3.1. Fermentation plants in Italy

Due to the above-mentioned limits, in Italy, currently, to date there are no pilot or industrial plants producing biohydrogen and biobutanol. However, these processes are widely investigated at a laboratory scale to improve the green energy transition. For example, recent Italian studies about biohydrogen production through dark fermentation are focusing on AFW such as olive waste mill water [98] and cheese whey [99], separately or in a combined process [100] or combined with fruit waste [101]. At the laboratory scale, the Italian research about biobutanol production focuses attention on the choice of the feedstock (mostly lignocellulosic substrates such as forestry residues, wood-pulp and wood-waste, olive brash residues, crop residues as branches and foliage) [102]. The downstream process and specifically on the thermodynamic framework to properly describe the phase equilibrium conditions involved in the process and the energy required [103].

In Italy, bioethanol is produced by Versalis, a chemical company owned by Eni S.p.A. that operates nationally and internationally in basic and intermediate chemicals, plastics, rubber, and chemistry from renewable sources. Versalis has three plants in Italy located in Crescentino (Piedmont, Nothern Italy), Porto Torres (Sardinia, Southern Italy), and Porto Marghera (Veneto, Northern Italy), and two research centers in Novara and Rivalta Scrivia (Piedmont, Northern Italy). The Crescentino plant was restarted in 2021 and is the world's first example of an industrial application of the PROESA® technology to produce bioethanol from biomass. The plant can process 200,000 tonnes of biomass each year, for a maximum production capacity of approximately 25,000 tonnes of bioethanol per year. The Crescentino site produces bioethanol defined as 'advanced' following the European Renewable Energy Directive RED II, a fuel from renewable raw material to be used in blends with petrol to promote sustainable mobility. Bioethanol is obtained from lignocellulosic biomass that does not compete with the food chain and its sustainability is certified according to the voluntary ISCC-EU (International Sustainability and Carbon Certification) scheme. The collection of biomasses in areas close to the plant promotes a sustainable short supply chain. The simplified process flow diagram of the Crescentino plant consists of biomass collection, thermal and enzymatic pre-treatments, fermentation with yeast, distillation, and concentration. The wastewater deriving from pre-treatment units and fermentation is treated through anaerobic digestion to produce biogas and the residual lignin is used to support energetically the plant. Hence the plant is energetically self-sufficient.

Furthermore, in response to the COVID-19 pandemic scenario, bioethanol was used to produce the Invix® brand hand and surface disinfectant, a bioethanol-based medical-surgical aid authorized by the Italian Ministry of Health. The plant is an example of sustainable enterprise and circularity, for four reasons: (1) it is self-energy sustainable due to the production of renewable electricity and steam from the thermoelectric plant, which is fuelled by short-chain biomass; (2) the plant has a water treatment system that allows the organic fraction contained in it to be recovered to produce biogas, which is used to produce steam; (3) it can purify the process-water used and (4) the lignin is used as an additional fuel in the biomass thermoelectric plant.

4.4. Bioplastic production

Plastic material is defined as bioplastic if it is either biobased, biodegradable, or features both properties. Biodegradability is defined as achieving 90 % decomposition within six months under specific conditions, including exposure to microorganisms (bacteria, microalgae, fungi), oxygen, humidity, and heat, typically within an industrial composting facility. The global bioplastics market size was estimated at 8.51 billion euros in 2020, with a projected annual growth rate of 17.1 % from 2021 to 2028 [104]. Interest in producing bioplastics from AFW has grown, although data on the most produced AFW-derived bioplastics varies. The most studied and produced bioplastics made from AFW include polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based blends, and cellulose-derived bioplastics.

PLA is a biodegradable thermoplastic produced from feedstock such as corn, sugarcane, or other starch-rich crops, which are hydrolysed (via enzymatic or acid hydrolysis), to break down the starches into sugars, and then the released sugars are fermented through lactic acid bacteria to produce the lactic acid. The lactic acid produced during fermentation needs to be purified to remove impurities and by-products [105]. This polymerisation process can be done through condensation-polymerization or ring-opening polymerization. The PLA material is used in manufacturing processes such as injection molding, extrusion, or thermoforming to create a wide range of products, including packaging materials, disposable cutlery, textiles, and more. Lactic acid yields are 0.34–0.60 g/g of xylo-oligosaccharides waste from corncob [106], 0.65–0.89 g/g of wheat corn [107] [107]and 0.29–0.33 g/g of mixed food waste [108].

PHA are biodegradable polymers produced through microbial fermentation of organic waste, such as whey, molasses, glycerol, cellulosic material, and waste oil. These feedstocks are fermented under nutrient-limited conditions with an excess of carbon [109]. The selected AFW may undergo pretreatment to enhance its biodegradability. Various microorganisms, including bacteria from the genera *Cupriavidus*, *Pseudomonas*, or *Azotobacter* are commonly used for PHA production. During fermentation, the microorganisms convert sugars from the biomass into PHA, a storage material within their cells [110]. At the end of fermentation, PHA is purified to remove impurities and residual components, yielding a high-quality product.

This refined PHA can be processed into pellets, sheets, or fibers, through techniques like extrusion, injection molding, or film casting [109]. The PHA is then used in manufacturing processes to produce a wide range of biodegradable products, including packaging materials, and agricultural films.

Starch blends are biodegradable materials produced from crop residues. These blends are produced by extracting starch from AFW through wet or dry milling and then combing it with other biodegradable polymers to improve properties, like flexibility [111]. Ongoing research and innovation enhance the reduction of environmental and economic impacts of starch-based biodegradable materials derived from various biowaste~~,~~ including manure, food industry leftovers, wastewaters, lignocellulosic biomass, crops, and algae [112]. Starch is the primary form of carbohydrates in plants and is usually stored in granules ranging from 1 μm to 100 μm in diameter, with various shapes varying by plant type. In 2021, starch blends accounted for 16.4 % of global bioplastics production [113]. Novamont S.p.A. was a leading producer of Mater-Bi, a starch-based bioplastic, in 2014.

Starch is applied in textiles, paper, and bioplastic formulations, enhancing thermal stability and biodegradability when it is blended with synthetic polymers. However, the starch blend has two main drawbaks: it is water sensitive, and it has poor mechanical properties that require to be considered and currently are manged through techniques like plasticization and blending with other polymers [113].

4.4.1. Bioplastic production plants in Italy

The market of bioplastic can be segmented based on product type (biodegradable or non-biodegradable) and application (packaging, consumer goods, textiles, etc.). In Italy, approximately 275 companies operate in the bioplastics sector, employing a total of 2645 workers [114]. The companies can be categorized into four groups: 1. basic and intermediate chemical manufacturers, 2. granule producers and distributors, 3. first-stage transformation operators, and 4. second-stage transformation operators. In 2019, the overall production volume exceeded 100,000 tonnes for the first time, representing an increase of 14 % compared to 2018. In terms of products, packaging remains the largest application sector for bioplastics, representing nearly 47 % of the total market in 2020. In Italy, major bioplastics manufacturers include Novamont S.p.A., offering a variety of everyday products composed of bio-based materials, BetaLife S.r.l., specializing in biodegradable and compostable products, and Agromateriae S.r.l., producing new bioplastics from AFW. Process information is not available for these companies, but some details about products and the company's visions are following.

The company BetaLife S.r.l. based in Jesi (Central Italy) produces biodegradable and compostable bioplastic materials with PLA, which is derived from sugarcane or glucose, substituting traditional plastics in a significant portion of their production. BetaLife S.r.l. manufactures bioplastic-based yogurt pots, plates and cutlery, fruit, and vegetable pots, cups, golf tees, and trays. Under optimal conditions of humidity (65 %-95 %), these items have a composting time of 50 days. If left in the soil, degradation times are 15 months if left on the surface, 24 months when buried, and 48 months dispersed in water, without releasing hazardous pollutants. These time frames are considerably less than the 100 years from traditional fossil fuel-based plastic.

AgroMateriae S.r.l. patented application for WinePlastics Filler (WPL) in 2019 and was accredited as an innovative startup by the University of Modena, aiming to scale up its process to industrial levels. WPL is a powder obtained through green processes from viticultural waste. This biofiller is a semi-finished product that can be blended from 5 % to 60 % with all existing plastics and bioplastics. Novamont S.p.A. was established in 1990 by the Montedison Group and it is a chemical company located in Novara and Terni (Northern-Central Italy). Novamont S.p.A. is specialised in bioplastic production and integrates chemistry and agriculture in a biorefinery system, promoting social, economic, and environmental advantages. The company produces three main products from agricultural feedstocks: Mater-Bi, Matrol-Bi, and CELUS-BI. Mater-Bi comprises thermoplastics derived from corn starch, cellulose, and vegetable oils, offering biodegradable and compostable properties. Mater-Bi is used to create biodegradable bags for shopping and organic waste collection. Matrol-Bi, a bio-lubricant oil, is produced from renewable agricultural feedstocks, possessing technical properties like fossil fuels but with the added benefit of biodegradability. CELUS-BI, a cosmetic product with biodegradable micro granules, is utilized in the production of eco-friendly moisturizers, shampoos, foundation creams, and lipsticks.

5. Emerging processes

AFW valorisation may also involve novel approaches that focus on the bioconversion of low-value components into more economically interesting compounds (i.e. proteins, biopolymers, biofuels). These processes, currently, are not largely exploited but they may represent an alternative in the near future to the solutions presented above and involve the exploitation of various organisms, including bacteria, fungi and even insects. In the following paragraphs, a brief overlook of the most promising biological agents for biotransformation and valorization of AFW is provided along with the existing plants in the Italian scenario

(Fig. 3(b)).

5.1. Bacteria and fungi-based processes

The role of bacteria in the AFW valorisation through fermentative processes to obtain biogas, biofuel, and bioplastic has been previously analysed (Sections 3.2, 4.3, and 4.4), but further applications, such as their exploitation to produce novel organic materials are promising [115]. Kee and colleagues [115] reviewed the products of microbial transformations and divided them into three categories: biopolymers, biosurfactants, and enzymes.

Biopolymers are similar to the previously described PHA (paragraph 4.4). Biosurfactants are more eco-friendly, biodegradable, and stable than synthetic ones derived from petroleum, and they can be biosynthesised by bacteria on a wide variety of AFW, such as potato peels, sugarcane bagasse, and molasse, or even tuna by-products. Lastly, enzymes produced by microorganisms are exploited for the degradation of lignocellulosic waste to obtain various monosaccharide sugars, lactic acid, phenolic compounds, and even precursor molecules that can have further applications.

Fungi are the other microorganisms that are suitable for inclusion in circular economy processes [116]. A growing trend in the number of published papers from 1991 to 2021 on fungal biotechnologies, gene editing, genomics, and mycoremediation underlines how promising and partially unknown is the world of fungi, which is also currently considered still too largely understudied and underutilised [117]. The remarkable variety of fungal and yeast species that can be grown on AFW is linked to the production of countless substances and molecules with possible applications in several fields such as the extraction of chitosan from fungi grown on wastes from potato chips processing or soybean processing residues [118]. The use of fungal metabolites or biomass for industrial applications is known as fungal white biotechnology: they can constitute an important resource for many products, including innovative and sustainable ones: applied fungal biotechnology can be used for food, feed, biocontrol, bioenergy, chemicals, pharmaceuticals, detergents, enzymes, proteins, paper and pulp, textiles, construction materials, and lastly for the automotive and transportation industries.

Apple pomace, olive mill wastewater, wheat straw, and walnut pericarp are a few examples of agricultural wastes that can be used to grow fungi [116] but also substrates characterised by higher levels of lignocellulosic biomass such as inedible plant material and maize stover are available options [119]. Fungi can also be involved in mycoprotein production as a meat substitute, using AFW with low-cost innovative techniques [120]. Another promising frontier for the practical application of fungi is the development and production of more efficient and sustainable batteries made up of these microorganisms [117], in a world that is becoming progressively more dependent on electricity and electrical power storage.

5.1.1. Bacteria and fungi industrially bred on biomasses in Italy

There are two Italian companies exploiting bacteria and fungi on plant biomass: Biofaber and Albini Group.

Biofaber is the first start-up created in collaboration with the University of Salento and is based in Mesagne (Southern Italy). Biofaber uses microorganisms to produce hydrophobic material. In particular, bacteria and fungi, naturally present in AFW, bioconvert the cellulose in a water medium where sugar is added. The products obtained are biogel, healing bandages, wellness masks, and a leatherette that can be used in various sectors such as leather goods, automotive, furniture, and fashion design.

Albini Group is based in Bergamo (Northern Italy) and is one of the companies that are exploiting bacteria to produce pigments for textile dyeing in collaboration with an Indian start-up (KBCols) and a British company (Colorifix). The production of these pigments takes place in a fermenter where the bacteria digest sugars and plant by-products. According to the Albini Group website, this firm is working on a project called "Hyphae", still in the development phase, that focuses on fungi such as *Fusarium* spp. for pigment production, in collaboration with BGreen Technologies, a start-up company from Lombardy (Northern Italy). The pigment production is patent-protected and revolves around the stimulation of the biosynthesis and the pre-extraction of pigment directly during fermentation. The production specifications or the raw materials used to develop the fungal mass are not disclosed.

Several projects for the recycling of AFW, using yeasts to process waste from wheat, rice, maize, and cassava chains to obtain food, feed, or methane, have been developed by the International Flavors and Fragrances (IFF). The company, based in the United States with global branches, including Italy, focuses on food, beverage, health, biosciences, and scents.

The Smart Protein project, led by the University of Cork (Ireland), aims to produce proteins beneficial for the economy, environment, biodiversity, and consumer safety. Among the several research lines they are following, one is related to the production of biomass from fungi using waste from pasta, bread, and beer chains. The project is funded by the EU, and it is in partnership with a prominent Italian pasta company. While the mycoprotein-producing sector is emerging in Italy, in other European countries, such as the Netherlands and Sweden, established companies like ENOUGH and Mycorena, are present and are showing potential for scaling up their production. ENOUGH plans to increase production from 10,000 to 60,000 tonnes annually in the next five years, utilizing wheat processing by-products. Mycorena is part of the European LIFE RE: FOOD project (2021–2024) and aims to enhance vegan fungi-based protein production using oat and wheat processing biowaste.

5.2. Insects-based processes

The rearing of insect species has a long tradition but it was limited to a few selected species (i.e., *Apis mellifera,* and *Bombyx mori*). Insects may constitute alternatives to soy and fishmeal as protein sources for animal feed or even be "novel foods" for human consumption. The European Union is currently outlining the regulatory framework to allow and regulate their breeding and processing. In the EU, insect rearing involves 3 species of crickets (*Acheta domesticus*, *Gryllus assimilis,* and *Gryllodes sigillatus),* 2 species of Coleoptera (*Alphitobius diaperinus* and *Tenebrio molitor),* 2 species of Diptera (*Hermetia illucens* and *Musca domestica)* and one species of Lepidoptera *(Bombyx mori,* the most recently authorised). These species are considered farming animals and are assimilated to any other animal species that is authorised for human consumption thus, they must be reared in facilities authorised and complying with food hygiene standards [121]. Therefore, also all the matrices used as insect feed are subjected to the governing regulations of the feed sector. Processed animal proteins from these eight species can be added to feed for fish, poultry, and pigs.

A novel and promising research field in Western countries is based on the use of insects in the degradation and bioconversion of organic matrices into economically interesting and useful products. Insects, depending on the species, feed on several substrates. Rearing insects using AFWs without any specific destination for food and feed production can make waste management more sustainable [122]. Unluckily, only a few of the aforementioned species are of interest as converters of AFW into high-value-added products [123].

AFW may be used as long as there are scraps or by-products and not waste, thus also their management is of paramount importance. However, the legislation is ongoing, and new substrates will likely be authorised. Examples of not allowed wastes include animal dejections, meat by-products, and slaughterhouse wastes. Independently of current EU legislation, AFW tested for *M. domestica* farming were poultry manure [124] and fresh and pretreated manure [125]. *M. domestica* is of significant interest in exploiting and managing the manure of different farmed animals but, as above reported, this is currently not possible on a pilot and industrial level according to EU legislation.

The yellow mealworm beetle (*T. molitor*) can be reared on substrates mixed with decayed vegetable garden waste, horse manure, cattle manure [126], and spent mushroom substrate [127].

Studies have demonstrated that *T. molitor* larvae can thrive on various plant-based matrices, including grape seed flour, fava bean hulls, and psyllium seed husks [128]. This species is regarded as one of the most promising candidates for industrial-scale rearing in the European market as feed and food. However, its relatively long life cycle (about 185 days at 23 °C) can vary significantly depending on the substrate, presenting a notable challenge [129].

Large industrial insect breeding companies are already present in Europe, such as Ynsect, which is based in France This company breeds *T. molitor* but matrices involved to brewing it are not disclosed. The most probable matrix is cereal bran and/or similar bran supplemented with fruit and vegetables such as potatoes and carrots.

Another promising species is *H. illucens*, the black soldier fly (BSF), an insect whose larvae are saprophytes and can feed efficiently on a wide variety of organic matrices as long as they have a moisture content of around 65 % without free water available. AFW that can potentially be used to rear *H. illucens* in a circular economy perspective are numerous, like fruit waste [130], vegetable waste [131], corn stover milk [132], cheese industry waste [133], and bakery waste [134]. It has to be noted that it can be quite different to evaluate *H. illucens* performances using a given substrate in a laboratory or a small-scale test compared to using the same AFW in industrial plants. Challenges stem either from the current regulations (e.g., in the EU the use of manure of any origin is not allowed) but also from the logistic aspects of the supply chain for the selected waste that should be considered in terms of the quantities required, transport, delivery logistics, and waste management at both the producing and the receiving farms. Moreover, an important factor in optimizing larval growth is the waste mix, which must consider the nutritional needs of the species, like the optimal crude protein to non-fiber carbohydrate ratio and crude protein to gross energy ratio [135]. Pilafidis et al. In 2022 [136] demonstrated that feeding *H. illucens* larvae with a mixture of wheat bran and wheat flour (high-quality food substrates) reached a higher weight in a shorter time than those reared on grass or animal manure (low-quality substrates). A recent study reported the development of a biorefinery process employing two insect species in a two-step approach: initial bioconversion of organic matrices using *T. molitor*, followed by treatment with *H. illucens* larvae[137]. Alternative bioconversion processes may involve an initial bacterial fermentation phase, succeeded by a treatment stage utilizing *H. illucens* larvae [138].

5.2.1. *Insects-based processes in Italy*

Transposition by Italian legislators of the European legislative framework is still ongoing; therefore, many companies that have shown interest in the insect breeding sector have to face the lack of regulations needed to define the boundaries in which they would operate. Nowadays insect breeders are considered operators in the primary feed sector according to the EC Reg 183/05 but they must be registered as non-primary feed business operators if, for example, they further process insects after harvest with treatments other than simple physical treatments.

The Italian Ministry of Health has integrated the platform of the Veterinary Information System with the Section 'Heliciculture and other invertebrates' in which, as of June 1st, 2023, in addition to snail breeding activities, it will be compulsory to register activities in which insects are reared and used for zootechnical purposes. However, the register does not currently record farm size, the amount, and the destination of the obtained products. Registration is in progress: at the end of February 2024, 11 insect farms were registered in this section: 6 of them rear house crickets, 2 *T. molitor*, 1 *H. illucens,* and 2 *B. mori*. The sector in Italy seems to be underdeveloped but promising after the definition of the legislative framework. There are no companies that rear *H. illucens* larvae for the large-scale feed market. Those active are small-sized and, they mainly focus on pet food. For example, Bugslife is probably the most structured company in the sector at the moment, and it is located in the Perugia province (Central Italy). In November 2023, they announced an expected production of 600 tons per year starting production in 2024. They currently have a pilot plant, and they are planning to build an industrial plant in Sardinia (Southern Italy). They have built an interesting stakeholder network that will assist them with AFW sourcing, production, and marketing. Regarding pilot plants for the production of *H. illucens* larvae on the Italian territory, the situation has significantly improved in recent years. The oldest plant is owned by Bef Biosystems, and it is a pilot bug farm in Casalnoceto (Northern Italy). In 2023, the company Energy Tre, located in Bondeno (Northern Italy) realised, in the framework of the project Flies4feed, a black soldier fly breeding prototype. The University of Basilicata, in the framework of the project "Exploitation of livestock waste through innovative technology based on the use of the bioconverting insect *H. illucens*", which ended in 2021, has developed a fully equipped biofactory for large-scale breeding of the insect *H. illucens* and the creation of a mobile and itinerant bioconversion unit to demonstrate the process of bioconversion of organic substrates. The system is based on a daily input ranging up to 50 kg of organic waste and produces 9 kg/day of larval biomass and 10 kg/day of frass, which can be used as soil fertiliser for agriculture. The system uses a daily amount of substrate ranging up to 50 kg of organic used as a soil fertiliser for agriculture. This mobile bioconversion unit is currently located at the University of Basilicata (Southern Italy) and is being used for experimental tests, after having been used in several farms during the project. Lastly, a proof-of-principle fly larvae biorefinery for biopolymer plastic production is being created at the University of Bologna (Northern Italy) as part of an EU-funded project BioLaMer coordinated by Green Trinity College of Dublin.

6. Future directions according to economic and environmental feasibility

This paragraph analyses from economic and environmental perspectives the above-mentioned processes gathered according to TRL. This analysis is necessary since the lack of techno-economic-environmental feasibility studies. The International Energy Agency Bioenergy Task 42 defined biorefining as the sustainable processing of biomass into a spectrum of bio-based products and bioenergy. Second-generation (2 G) biorefineries convert waste biomass into valuable products and bioenergy. This approach reduced the reliance on food crops by promoting circular economy principles. Key sustainability factors include the feedstock's origin, the efficiency of the conversion process, and the value and environmental impact of the final products. 2 G biorefineries are made of three units: waste biomass (feedstock, such as AFW), process, and products.

To design a 2 G biorefinery, it's crucial to consider the availability of the waste biomass, including its quantity and seasonal variations. This information determines the optimal size of the plant and its location, which influences the organization of biomass collection and transportation [139]. Standardisation and quality control of AFW are key aspects for making such applications scalable and cost-effective in industrial processes [114].

The second pillar of the 2G-biorefinery is the conversion process of AFW, which concerns industrial, pilot, and emerging processes. The technical-environmental and cost-competitiveness of 2 G biorefinery depends on the balance between product quality, energy consumption, and waste generation. Industrial processes concern composting, AD, and combustion. Composting plants offer significant techno-economic and environmental benefits for AFW management. While initial investment costs can be substantial, long-term economic advantages include reduced waste disposal expenses and revenue from compost sales. These plants also serve as educational hubs, promoting waste management awareness and sustainable living within communities. However, addressing challenges like odour control, leachate management, and compost quality is crucial. Effective monitoring, management practices, and technological advancements can help mitigate these issues, ensuring the success of composting plants [140].

Another biochemical industrial process to treat AFW is AD. AD plants require capital investments of around 300 €/(ton/y) whereas the operational expenses (OPEX) range from about 80 €/(ton/y) [141]. If carbon capture is integrated into AD, the capital investment increases to 500 €/(ton/y) and the OPEX may double. However, this can significantly reduce the environmental impact of AD, bringing it closer to carbon neutrality [141]. AD is one of the few biochemical processes that is nowadays economically feasible on an industrial scale and offers environmental benefits by reducing landfill-related pollution and GHG emissions. However, AD of lignocellulosic AFW is not economically feasible due to the high pretreatment cost. While AD itself can be profitable, upgrading biogas to biomethane introduces economic uncertainties. Europe recorded a total of 1023 biomethane production facilities in 2021, particularly in France, Italy, and Denmark [42]. The second product of AD is digestate, a nutrient-rich product for fertiliser production. However, regulatory frameworks often fail to classify digestate-derived products, limiting their adoption, notably in regions with nutrient surpluses such as Southern Europe (i.e., Italy, and Northeastern Spain) [142].

Among thermochemical processes, combustion is employed at the industrial scale to generate heat and electricity, reducing waste volume and weight by at least 50 % [51]. Combustion processes require high temperature and pressure, [143], but it releases fewer GHG emissions than fossil fuel-based energy [144]. Direct combustion offers significant techno-economic potential due to its low cost and operating capacity. Kumar et al. in 2021 [141] reviewed the combustion costs in the EU and USA, stating that the capital cost ranges between 600 and 750 €/ton of waste processed. However, the cost may vary according to the variation in interest rate, local manufacturing, and taxing policy of the government. It has to be noted that combustion, despite higher pollutant emissions due to incomplete combustion and reactions with impurities, offers easier energy storage and transportation compared to other renewable energy sources like solar or wind [145]. The second group of analysed processes concerns fermentation, pyrolysis, and gasification, currently implemented at the pilot scale. Pyrolysis and gasification are in the starting commercialisation phase, and consequently, the cost of these processes is expensive. Kumar et al. in 2021 [141] reported that pyrolysis costs about 1100 €/dry ton of feedstock. The cost of electricity production through fast pyrolysis is in the range of 9–12.1 €/kWh, whereas via slow pyrolysis between 10.7 and 14.4 €/kWh. Pyrolysis oil, when blended with gasoline, requires a minimum fuel selling price of 0.89 €/L to offset production costs. Scaling up and commercialisation of pyrolysis technology depends on addressing research gaps, including feedstock quality, ash-volatile interactions, mixed biomass effects, and product upgrading, particularly for oil. Currently, the main commercialisation barrier for pyrolysis is the high capital cost of oil and gas upgrading processes. [146].

Gasification converts solid feedstock into syngas, which could produce liquid fuels, including ethanol and methanol, or could be used to produce energy. Gasification is considered a low-cost process, but it is facing technical issues like the production of tar, which blocks the filters and fuel lines, negatively affecting plant operations. Kumar et al., 2021 [141] stated that for a 1 MW plant, the capital investments of a gasifier are 372 €/kW. It is worth noting that, a coal gasifier of similar capacity costs twice as much as a biomass gasifier. This proves that biomass gasifiers could be economically effective when technical challenges are solved [147].

Fermentation could be employed to produce bioenergy (gas and liquid) and biomaterials like bioplastics. Even if the technology is available, there are still many challenges to make industrial biorefineries economically appealing, including high capital and operating costs, and low yield which limit the scaling-up issues. The pretreatment for making lignocellulosic sugars more accessible to enzymes is one of the biggest technical and economic bottlenecks [143]. The heterogeneous nature and composition of lignocellulosic biomass, coupled with the complex interaction between cellulose fibers and lignin, further complicates the industrialization of pretreatment. Factors such as cost, biomass type, energy consumption, chemical usage, and generation of inhibitory compounds must be carefully considered [148]. Strategies for cost reduction and improved enzymatic hydrolysis and microbial fermentation are needed. Genetic and metabolic engineering routes should be explored for increased yields and consequently cost-effectiveness. However, as it stands, fermentative biofuel production is not as cost-competitive as fossil-based fuels [149].

The environmental performances of fermentation, pyrolysis, and gasification of corn stover were compared to produce 1 GJ of energy, adopting the LCA methodology and CML 2001 methods [150]. Fermentation involves the conversion of corn stover into bioethanol, encompassing pretreatment, enzyme production, enzymatic hydrolysis and fermentation, product separation and recovery, wastewater treatment, burner operation, storage, and utilities. Pyrolysis comprised corn stover pretreatment, pyrolysis to crude oil, crude oil upgrading to the final product, and burner/boiler operations. Gasification of corn stover included pretreatment, gasification, water gas shift, product refining, and energy recovery stages. The study found that the climate change impact on the pyrolysis was 64.8 kg CO_2eq/GJ, significantly higher compared to the fermentation and gasification systems, which achieved 18.4 kg CO_2eq/GJ and 19.9 kg CO_2eq/GJ, respectively. These values can be attributed to the substantial hydrogen and ethanol requirements for upgrading the crude bio-oil in the pyrolysis system, highlighting the costly nature of oil upgrading processes.

Bioplastics, derived from AFW, offer an alternative to petroleum-based plastics. PHA and PLA have shown promise, but their commercialization and scalability face challenges. High production costs, due to processing AFW and low yields, hinder their cost-competitiveness, especially in price-sensitive markets. Additionally, bioplastics may not always match the performance and properties of conventional plastics, limiting their applications. The infrastructure for bioplastic manufacturing, distribution, and recycling is less developed than that for petroleum-based plastics. Separate processing facilities and collection systems are required for bioplastics, increasing costs and logistical complexity. Furthermore, biodegradable bioplastics necessitate appropriate composting facilities, which may not be widely available. Regulatory inconsistencies across regions regarding environmental certifications, compostability standards, and labeling requirements create uncertainty for bioplastic manufacturers and hinder market adoption. Clear and consistent regulatory frameworks are essential to support the growth of the bioplastics industry.

Few data are available on the environmental impact associated with fungi and insect production with AFW because the environmental consequences have been studied less. In particular, there is still a lack of a significant number of studies on the quantification of the emissions produced by insects. Indeed, very little experimental data regarding emissions from insect production are available and these data only refer to a very limited number of insect species [151].

The choice of the process and its commercialization depends on the regional demand for a product, policy support, and technology maturity. EU policy promotes the circular economy through financial incentives and laws and encourages the development of environmentally friendly and economically sustainable products and processes. Specifically, it could be mentioned the EU Programme and the sub-program, Circular Economy, and Quality of Life (Regulation 2018/1046 and 2021/783), together with the sub-program Climate Change Mitigation and Adaption, Nature, and Biodiversity. Funding is extremely important to find solutions for overcoming some technical problems (e.g. rapid degradation of biomass, transportation costs, etc.) and demonstrate the possibility of scaling up novel products and processes.

7. Conclusions

This review provides a comprehensive analysis of the potential for converting agro-food waste (AFW) into valuable products and energy, within the context of Italy's waste management and circular economy initiatives. By categorizing the processes into industrial-scale, pilot-scale, and emerging technologies, their current TRLs and the challenges associated with their implementation and scalability have been highlighted. Industrial-scale processes, predominantly located in the North of Italy, represent an immediate opportunity for stakeholders, emphasizing the need for continued support to expand these systems and integrate them further into the national network. These facilities are vital to Italy's circular economy framework, as they transform AFW into renewable resources, closing resource loops and reducing dependency on fossil-based systems. Pilot-scale processes are mostly found in the Central and Southern regions and, while demonstrating technical feasibility, face challenges related to cost-effectiveness and product scalability. Emerging technologies, including insect- and bacteria-based processes, bring unique potentiality for circularity and environmental sustainability. By utilizing biological mechanisms for waste conversion, these processes not only minimize environmental impact but also embody the principles of the circular economy by promoting closed-loop systems that regenerate natural resources. Although limited by low TRLs, these technologies offer a promising path forward for future applications in low-impact AFW management, highlighting areas where academia and early-stage industries can contribute to sustainable innovation. The findings of this review are essential for policymakers, who must consider the geographical distribution of facilities and support targeted investments in both emerging and pilot-scale technologies. The key findings of the review highlight that integrating AFW valorization processes into Italy's waste management framework demands a collaborative effort from researchers, industry leaders, policymakers, and local communities. Achieving successful integration requires a coordinated approach to boost these processes from pilot phases to full-scale deployment. Only through such collaboration can these efforts contribute to advancing sustainability goals and establishing robust circular economy models.

CRediT authorship contribution statement

Francesco Savorani: Writing – review & editing, Supervision, Project administration, Funding acquisition. **Tonia Tommasi:** Writing – review & editing, Supervision, Project administration, Formal analysis. **Filippo Cominelli:** Writing – original draft, Investigation. **Lucrezia Lamastra:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Maria Cristina Reguzzi:** Investigation, Funding acquisition. **Ilaria Chillin:** Writing – original draft, Investigation. **Giuseppe Toscano:** Writing – original draft, Investigation, Funding acquisition, Formal analysis. **Emanuele Mazzoni:** Writing – original draft, Investigation, Funding acquisition. **Erica Gagliano:** Writing – original draft, Investigation. **Manuela Mancini:** Writing – original draft, Investigation. **Adriana Del Borghi:** Writing – review & editing, Funding acquisition. **Francesca Stefania Freyria:** Writing – original draft, Investigation. **Martina Lenzuni:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Attilio Converti:** Writing – review & editing, Funding acquisition. **Francesca Demichelis:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] A.T. Hoang, A. Pandey, Z. Huang, S. Nižetić, A.T. Le, X.P. Nguyen, Biofuels an option for agro-waste management. in: Environ. Sustain. Biofuels, Elsevier, 2023, pp. 27–47, https://doi.org/10.1016/B978-0-323-91159-7.00011-4.
[2] Faostat, Land use statistics and indicators, FAO, 2022, https://doi.org/10.4060/cc0963en.
[3] FAOSTAT, Agricultural production statistics 2000–2021, Agric. Prod. Stat. 2000-2021 60 (2021) 1–17.2021.
[4] A.T. Hoang, A. Pandey, Z. Huang, S. Nižetić, A.T. Le, X.P. Nguyen, Biofuels an option for agro-waste management. in: Environ. Sustain. Biofuels, Elsevier, 2023, pp. 27–47, https://doi.org/10.1016/B978-0-323-91159-7.00011-4.
[5] C. Bastioli, L. Campanini, S. Fumagalli, M. Pini, A. Ragone, S. Capasso, C. Carreras, S. Trenti, S. Giusti, R.M. Vitulano, A. Cozzolino, La Bioeconomia in Europa, 2023. https://www.clusterspring.it/files/348/La Bioeconomia in Europa_Giugno 2023.pdf.
[6] A. Corona, M. Ambye-Jensen, G.C. Vega, M.Z. Hauschild, M. Birkved, Techno-environmental assessment of the green biorefinery concept: combining process simulation and life cycle assessment at an early design stage, Sci. Total Environ. 635 (2018) 100–111, https://doi.org/10.1016/j.scitotenv.2018.03.357.
[7] Neelancherry Remya, G. Bin, W. Alberto, Agricultural Waste to Value-Added Products Bioproducts and its Applications, Springer N, 2023. https://doi.org/10.1007/978-981-99-4472-9.
[8] R. Shinde, D.K. Shahi, P. Mahapatra, C.S. Singh, S.K. Naik, N. Thombare, A. K. Singh, Management of crop residues with special reference to the on-farm utilization methods: a review, Ind. Crops Prod. 181 (2022) 114772, https://doi.org/10.1016/j.indcrop.2022.114772.
[9] S. Liuzzi, C. Rubino, P. Stefanizzi, F. Martellotta, The agro-waste production in selected EUSAIR regions and its potential use for building applications: a review, Sustainability 14 (2022) 670, https://doi.org/10.3390/su14020670.
[10] B. Gao, Agric. Waste Value Added Prod. (2023), https://doi.org/10.1007/978-981-99-4472-9.
[11] G.M. Sonu, D. Rani, Pathania, R. Abhimanyu, S. Umapathi, Y.S. Rustagi, V. K. Huh, A. Gupta, V. Kaushik, Chaudhary, Agro-waste to sustainable energy: a green strategy of converting agricultural waste to nano-enabled energy applications, Sci. Total Environ. 875 (2023) 162667, https://doi.org/10.1016/J.SCITOTENV.2023.162667.
[12] M. Donner, R. Gohier, H. de Vries, A new circular business model typology for creating value from agro-waste, Sci. Total Environ. 716 (2020) 137065, https://doi.org/10.1016/J.SCITOTENV.2020.137065.
[13] M. Marttila, J. Havukainen, V. Uusitalo, L. Linnanen, M. Mikkilä, Multicriteria analysis of sustainable agri-food waste management for an agroecosystem in Finland, Front. Sustain. Food Syst. 8 (2024) 1–15, https://doi.org/10.3389/fsufs.2024.1426890.
[14] A. Sahoo, A. Dwivedi, P. Madheshiya, U. Kumar, R.K. Sharma, S. Tiwari, Insights into the management of food waste in developing countries: with special reference to India, Environ. Sci. Pollut. Res. 31 (2024) 17887–17913, https://doi.org/10.1007/s11356-023-27901-6.
[15] F. Boccia, P. Di Donato, D. Covino, A. Poli, Food waste and bio-economy: a scenario for the Italian tomato market, J. Clean. Prod. 227 (2019) 424–433, https://doi.org/10.1016/j.jclepro.2019.04.180.
[16] S. Venanzi, D. Pezzolla, L. Cecchini, M. Pauselli, A. Ricci, A. Sordi, B. Torquati, G. Gigliotti, Use of agricultural by-products in the development of an agro-energy chain: a case study from the Umbria region, Sci. Total Environ. 627 (2018) 494–505, https://doi.org/10.1016/j.scitotenv.2018.01.176.
[17] E. Tamburini, M. Gaglio, G. Castaldelli, E.A. Fano, Biogas from agri-food and agricultural waste can appreciate agro-ecosystem services: the case study of Emilia Romagna region, Sustain 12 (2020) 1–15, https://doi.org/10.3390/su12208392.
[18] E.A. Scano, M. Grosso, A. Pistis, G. Carboni, D. Cocco, An in-depth analysis of biogas production from locally agro-industrial by-products and residues. An Italian case, Renew. Energy 179 (2021) 308–318, https://doi.org/10.1016/j.renene.2021.07.050.
[19] S. Di Fraia, S. Fabozzi, A. Macaluso, L. Vanoli, Energy potential of residual biomass from agro-industry in a Mediterranean region of southern Italy (Campania), J. Clean. Prod. 277 (2020) 124085, https://doi.org/10.1016/j.jclepro.2020.124085.

[20] G.A. Buchner, K.J. Stepputat, A.W. Zimmermann, R. Schomäcker, Specifying technology readiness levels for the chemical industry, Ind. Eng. Chem. Res. 58 (2019) 6957–6969, https://doi.org/10.1021/acs.iecr.8b05693.
[21] U. De Corato, F.A. Cancellara, Measures, technologies, and incentives for cleaning the minimally processed fruits and vegetables supply chain in the Italian food industry, J. Clean. Prod. 237 (2019) 117735, https://doi.org/10.1016/j.jclepro.2019.117735.
[22] Ispra, Ispra, catasto nazionale dei rifiuti, Elenc. Naz. Delle Aut. e Comun. Inf. Fornite Dalle Amministrazioni Territ. (2024). ⟨https://www.catasto-rifiuti.isprambiente.it/index.php?pg=comautamm&advice=si⟩.
[23] M. Waqas, S. Hashim, S. Ahmad, R. Noor, M. Shoaib, A. Naseem, P.T. Hlaing, H. A. Lin, Composting processes for agricultural waste management, A Compr. Rev. (2023) 1–24.
[24] R. Phiri, S.M. Rangappa, S. Siengchin, Agro-waste for renewable and sustainable green production: a review, J. Clean. Prod. 434 (2024) 139989, https://doi.org/10.1016/j.jclepro.2023.139989.
[25] I. Gavilanes-Terán, J. Jara-Samaniego, J. Idrovo-Novillo, M. Bustamante, M. D. Pérez-Murcia, A. Pérez-Espinosa, M. López, C. Paredes, Agroindustrial compost as a peat alternative in the horticultural industry of Ecuador, J. Environ. Manag. 186 (2017) 79–87, https://doi.org/10.1016/j.jenvman.2016.10.045.
[26] I. Tabrika, E.H. Mayad, J.N. Furze, M. Zaafrani, K. Azim, Optimization of tomato waste composting with integration of organic feedstock, Environ. Sci. Pollut. Res. 28 (2021) 64140–64149, https://doi.org/10.1007/s11356-020-12303-9.
[27] K. Azim, Y. Faissal, B. Soudi, C. Perissol, S. Roussos, I. Thami Alami, Elucidation of functional chemical groups responsible of compost phytotoxicity using solid-state ^{13}C NMR spectroscopy under different initial C/N ratios, Environ. Sci. Pollut. Res. 25 (2018) 3408–3422, https://doi.org/10.1007/s11356-017-0704-9.
[28] B. Sun, Z. Bai, Y. Li, R. Li, M. Song, S. Xu, Emission mitigation of CH 4 and N 2 O during semi-permeable membrane covered hyperthermophilic aerobic composting of livestock manure, J. Clean. Prod. 379 (2022) 134850, https://doi.org/10.1016/j.jclepro.2022.134850.
[29] J. Chen, C. Jin, S. Sun, D. Yang, Y. He, P. Gan, W. Gerald, Y. Ma, W. He, G. Li, Resources, conservation & recycling recognizing the challenges of composting: critical strategies for control, recycling, and valorization of nitrogen loss, Resour. Conserv. Recycl. 198 (2023) 107172, https://doi.org/10.1016/j.resconrec.2023.107172.
[30] S. Wang, Y. Wu, Hyperthermophilic composting technology for organic solid waste treatment, Recent Res. Adv. Trends (2021) 1–11.
[31] J. Tang, X. Li, W. Zhao, Y. Wang, P. Cui, R.J. Zeng, to simultaneously enhance the maturity of aerobic composting and mitigate greenhouse gas emissions, Bioresour. Technol. 279 (2019) 234–242, https://doi.org/10.1016/j.biortech.2019.01.140.
[32] Biogas Italian Composting and, Annual Report on Biowaste Recycling, 2017. https://www.compost.it/wp-content/uploads/2019/08/Rapporto-CIC-2017-Eng-v-2.6-web-version.pdf. .
[33] C. Bruni, C. Akyol, G. Cipolletta, A.L. Eusebi, D. Caniani, S. Masi, J. Colon, F. Fatone, Decentralized community composting: past, present and future aspects of Italy, Sustain 12 (2020), https://doi.org/10.3390/SU12083319.
[34] ECN Data Report 2022, Compost and digestate for a circular bioeconomy-Overview of bio-waste collection, treatment and markets across Europe, 2022. https://doi.org/ISBN 978-3-9820825-1-6.
[35] M. Collotta, G. Tomasoni, ScienceDirect ScienceDirect The environmental sustainability of biogas production with small sized plant, Energy Procedia 128 (2017) 38–45, https://doi.org/10.1016/j.egypro.2017.09.012.
[36] F.R. Amin, H. Khalid, H.M. El-Mashad, C. Chen, G. Liu, R. Zhang, Functions of bacteria and archaea participating in the bioconversion of organic waste for methane production, Sci. Total Environ. 763 (2021) 143007, https://doi.org/10.1016/j.scitotenv.2020.143007.
[37] A. Abbassi-guendouz, D. Brockmann, E. Trably, C. Dumas, J. Delgenès, J. Steyer, R. Escudié, Bioresource Technology Total solids content drives high solid anaerobic digestion via mass transfer limitation, Bioresour. Technol. 111 (2012) 55–61, https://doi.org/10.1016/j.biortech.2012.01.174.
[38] A.A. Pesantes, E.P. Carpio, E.J. Mart, G. Xiomar, Anaerobic digestion for producing renewable energy — the evolution of this technology in a new uncertain scenario 23 (2021) 1.
[39] G. Mitraka, K.N. Kontogiannopoulos, M. Batsioula, G.F. Banias, A.I. Zouboulis, P. G. Kougias, A Comprehensive Review on Pretreatment Methods for Enhanced Biogas Production from Sewage Sludge, (2022).
[40] M. Lenzuni, A. Converti, A. Alberto, Bioresource Technology From laboratory- to industrial-scale plants: future of anaerobic digestion of olive mill solid wastes, Bioresour. Technol. 394 (2024) 130317, https://doi.org/10.1016/j.biortech.2024.130317.
[41] G. Náthia-Neves, M. Berni, G. Dragone, S.I. Mussatto, T. Forster-Carneiro, Anaerobic digestion process: technological aspects and recent developments, Int. J. Environ. Sci. Technol. 15 (2018) 2033–2046, https://doi.org/10.1007/s13762-018-1682-2.
[42] WBA, World Biogas Association, (2023). ⟨https://www.worldbiogasassociation.org/⟩.
[43] C.F. a Sergio Piccinini a, Mariangela Soldano a, La produzione di biogas del settore agricolo in Italia, (2011). ⟨https://agriregionieuropa.univpm.it/it/content/article/31/24/la-produzione-di-biogas-del-settore-agricolo-italia⟩.
[44] G. Chinnici, R. Selvaggi, M.D. Amico, B. Pecorino, Assessment of the potential energy supply and biomethane from the anaerobic digestion of agro-food feedstocks in Sicily, Renew. Sustain. Energy Rev. 82 (2018) 6–13, https://doi.org/10.1016/j.rser.2017.09.018.
[45] F. Battista, N. Frison, D. Bolzonella, Energy and nutrients' recovery in anaerobic digestion of agricultural biomass: an Italian perspective for future applications, Energies 12 (2019), https://doi.org/10.3390/en12173287.
[46] M.C.D. Salangsang, M. Sekine, S. Akizuki, H.D. Sakai, N. Kurosawa, T. Toda, Effect of carbon to nitrogen ratio of food waste and short resting period on microbial accumulation during anaerobic digestion, Biomass-.-. Bioenergy 162 (2022) 106481, https://doi.org/10.1016/j.biombioe.2022.106481.
[47] S. Croce, Q. Wei, G.D. Imporzano, R. Dong, F. Adani, Anaerobic digestion of straw and corn stover: The effect of biological process optimization and pre-treatment on total bio-methane yield and energy performance, Biotechnol. Adv. 34 (2016) 1289–1304, https://doi.org/10.1016/j.biotechadv.2016.09.004.
[48] B. Hashemi, S. Sarker, J.J. Lamb, K.M. Lien, Yield improvements in anaerobic digestion of lignocellulosic feedstocks, J. Clean. Prod. 288 (2021) 125447, https://doi.org/10.1016/j.jclepro.2020.125447.
[49] John Wiley & Sons Ltd, Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power, 2019. https://doi.org/10.1002/9781119417637.
[50] S. Mishra, R.K. Upadhyay, Review on biomass gasification: Gasifiers, gasifying mediums, and operational parameters, Mater. Sci. Energy Technol. 4 (2021) 329–340, https://doi.org/10.1016/j.mset.2021.08.009.
[51] E.V.S. Caillat, Large-scale biomass combustion plants: an overview, Biomass-.-. Combust. Sci. Technol. Eng. 9 (2013) 189–224, https://doi.org/10.1533/9780857097439.3.189.
[52] M. Faizan, H. Song, Critical review on catalytic biomass gasification: state-of-Art progress, technical challenges, and perspectives in future development, J. Clean. Prod. 408 (2023) 137224, https://doi.org/10.1016/J.JCLEPRO.2023.137224.
[53] ENAMA, Biomasse ed energia – Disponibilità delle biomasse, (2011) 1–144. ⟨https://www.progettobiomasse.it/it/pdf/studio/p1c2.pdf⟩.
[54] fiper (2020), Report impianti teleriscaldamento a biomassa Fiper 2020, 2021.
[55] G. Toscano, E. Leoni, G. Feliciangeli, D. Duca, M. Mancini, Application of ISO standards on sampling and effects on the quality assessment of solid biofuel employed in a real power plant, Fuel 278 (2020) 118142, https://doi.org/10.1016/j.fuel.2020.118142.
[56] T. Varzakas, G. Zakynthinos, F. Verpoort, Plant food residues as a source of nutraceuticals and functional foods, Foods 5 (2016) 1–32, https://doi.org/10.3390/foods5040088.
[57] S.S.M.Sujeet Yadav, A complete review based on various aspects of pulverized coal combustion, Enerny Res. (2019), https://doi.org/10.1002/er.4395.
[58] A2A, Waste-to-energy plants help us to close the integrated waste management cycle and to return new energy and heat to urban areas, (2024). ⟨https://www.gruppoa2a.it/en/about-us/our-plants/waste-cycle/waste-to-energy⟩ (accessed August 31, 2024).
[59] K. Thu, T. Reungpeerakul, R. Yamsaengsung, C. Sangwichien, Model. Optim. Oper. Parameters Fast Pyrolysis Palm. Oil Biomass-.-. Wastes Based Differ. Kinet. Schemes (2021) 1–11, https://doi.org/10.1002/ep.13717.
[60] X. Yang, W. Ng, B. Shu, E. Wong, G. Hun, C. Wang, Characterization and ecotoxicological investigation of biochar produced via slow pyrolysis: effect of feedstock composition and pyrolysis conditions, J. Hazard. Mater. 365 (2019) 178–185, https://doi.org/10.1016/j.jhazmat.2018.10.047.
[61] M. Zhou, K. Govindan, X. Xie, How fairness perceptions, embeddedness, and knowledge sharing drive green innovation in sustainable supply chains: an equity theory and network perspective to achieve sustainable development goals, J. Clean. Prod. 260 (2020) 120950, https://doi.org/10.1016/j.jclepro.2020.120950.
[62] Z. Ma, J. Wang, C. Li, Y. Yang, X. Liu, C. Zhao, D. Chen, New sight on the lignin torrefaction pretreatment: relevance between the evolution of chemical structure and the properties of torrefied gaseous, liquid, and solid products, Bioresour. Technol, Bioresour. Technol. 288 (2019) 121528, https://doi.org/10.1016/j.biortech.2019.121528.
[63] C. Lu, X. Zhang, Y. Gao, Y. Lin, J. Xu, C. Zhu, Parametric study of catalytic co-gasi fi cation of cotton stalk and aqueous phase from wheat straw using hydrothermal carbonation, Energy 216 (2021) 119266, https://doi.org/10.1016/j.energy.2020.119266.
[64] M. He, Z. Xu, Y. Sun, P.S. Chan, I. Lui, D.C.W. Tsang, Bioresource Technology Critical impacts of pyrolysis conditions and activation methods on application-oriented production of wood waste-derived biochar, Bioresour. Technol. 341 (2021) 125811, https://doi.org/10.1016/j.biortech.2021.125811.
[65] S. Vendra, S. Chaturvedi, V.C. Dhyani, G. Kasivelu, Bioresource Technology Pyrolysis temperature influences the characteristics of rice straw and husk biochar and sorption / desorption behaviour of their biourea composite, Bioresour. Technol. 314 (2020) 123674, https://doi.org/10.1016/j.biortech.2020.123674.
[66] H. Luo, B. Wang, J. Jian, F. Wu, L. Peng, D. Wang, Stress-release design for high-capacity and long-time lifespan aqueous zinc-ion batteries, Mater. Today Energy 21 (2021) 100799, https://doi.org/10.1016/j.mtener.2021.100799.
[67] W. Cai, Z. Luo, J. Zhou, Q. Wang, A review on the selection of raw materials and reactors for biomass fast pyrolysis in China, Fuel Process. Technol. 221 (2021) 106919, https://doi.org/10.1016/j.fuproc.2021.106919.
[68] Y. Al Haj, S. Mousavihashemi, D. Robertson, M. Borghei, T. Pääkkönen, O. J. Rojas, E. Kontturi, T. Kallio, J. Vapaavuori, Biowaste-derived electrode and electrolyte materials for flexible supercapacitors, Chem. Eng. J. 435 (2022), https://doi.org/10.1016/j.cej.2022.135058.
[69] S. Kant, A.K. Palai, A. Kumar, R. Kant, A. Kumar, V. Kumar, Y. Yang, Bioresource Technology Trends in renewable energy production employing biomass-based biochar, Bioresour. Technol. 340 (2021) 125644, https://doi.org/10.1016/j.biortech.2021.125644.

[70] T. Kan, V. Strezov, T. Evans, J. He, R. Kumar, Q. Lu, Catalytic pyrolysis of lignocellulosic biomass: a review of variations in process factors and system structure, Renew. Sustain. Energy Rev. 134 (2020) 110305, https://doi.org/10.1016/j.rser.2020.110305.

[71] Y. Li, K. Li, B. Hu, Z. xi Zhang, G. Zhang, S. yu Feng, T. peng Wang, Q. Lu, Catalytic fast pyrolysis of cellulose for selective production of 1-hydroxy-3,6-dioxabicyclo[3.2.1]octan-2-one using nickel-tin layered double oxides, Ind. Crops Prod. 162 (2021) 113269, https://doi.org/10.1016/j.indcrop.2021.113269.

[72] G. Venkatesh, K.A. Gopinath, K.S. Reddy, B.S. Reddy, M. Prabhakar, C. Srinivasarao, V.V. Kumari, V.K. Singh, Characterization of biochar derived from crop residues for soil amendment, carbon sequestration and energy use, Sustain 14 (2022), https://doi.org/10.3390/su14042295.

[73] J. Makwana, A.D. Dhass, P.V. Ramana, D. Sapariya, D. Patel, An analysis of waste / biomass gasification producing hydrogen-rich syngas: a review, Int. J. Thermofluids 20 (2023) 100492, https://doi.org/10.1016/j.ijft.2023.100492.

[74] P. Basu, Biomass Gasification, pyrolysis, and torrefaction practical design and theory. Second Edi (2013).

[75] M. Dudyński, J.C. Van Dyk, K. Kwiatkowski, M. Sosnowska, Biomass gasification: influence of torrefaction on syngas production and tar formation, Fuel Process. Technol. 131 (2015) 203–212, https://doi.org/10.1016/j.fuproc.2014.11.018.

[76] S. Raza, M. Naqvi, S. Ali, A. Taqvi, F. Iqbal, A. Inayat, A. Hussain, M. Taqi, M. Ayoub, M. Shahbaz, N. Aishah, S. Amin, Agro-industrial residue gasi fi cation feasibility in captive power plants: a South-Asian case study, Energy 214 (2021) 118952, https://doi.org/10.1016/j.energy.2020.118952.

[77] C.E. Agu, L.A. Tokheim, C. Pfeifer, B.M.E. Moldestad, Behaviour of biomass particles in a bubbling fluidized bed: a comparison between wood pellets and wood chips, Chem. Eng. J. 363 (2019) 84–98, https://doi.org/10.1016/j.cej.2019.01.120.

[78] H. Gu, Y. Tang, J. Yao, F. Chen, Study on biomass gasi fi cation under various operating conditions, J. Energy Inst. 92 (2019) 1329–1336, https://doi.org/10.1016/j.joei.2018.10.002.

[79] T. Jankovi, A.J.J. Straathof, A.A. Kiss, Adv. Downstr. Process. Bioethanol Syngas Ferment. 322 (2023), https://doi.org/10.1016/j.seppur.2023.124320.

[80] J. Daniell, M. Köpke, S.D. Simpson, Commercial Biomass Syngas Fermentation, 2012. https://doi.org/10.3390/en5125372.

[81] V. Ahuja, A.K. Bhatt, B. Ravindran, Y. Yang, S.K. Bhatia, A Mini Rev. Syngas Ferment. Bio-Alcohol. Curr. Status Chall. (2023) 1–21.

[82] E. Kurkela, P. Simell, P. Ståhlberg, 2016, Development of novel fixed-bed gasification for biomass residues and agrobiofuels novel heating hea plant ting pla nt novel, (2016).

[83] N. Cerone, F. Zimbardi, Gasification of Agroresidues for Syngas Production, (2018). https://doi.org/10.3390/en11051280.

[84] S. Piazzi, X. Zhang, F. Patuzzi, M. Baratieri, Techno-economic assessment of turning gasification-based waste char into energy: a case study in South-Tyrol, Waste Manag 105 (2020) 550–559, https://doi.org/10.1016/j.wasman.2020.02.038.

[85] M. Villarini, E. Bocci, A. Di Carlo, E. Savuto, V. Pallozzi, The case study of an innovative small scale biomass waste gasification heat and power plant contextualized in a farm, Energy Procedia 82 (2015) 335–342, https://doi.org/10.1016/j.egypro.2015.11.790.

[86] I. Chung, J. Kim, K. Lee, S. Park, J. Lee, N. Son, Y. Jin, S. Kim, Geographic authentication of Asian rice (Oryza sativa L.) using multi- elemental and stable isotopic data combined with multivariate analysis, Food Chem. 240 (2018) 840–849, https://doi.org/10.1016/j.foodchem.2017.08.023.

[87] A. Devi, A. Singh, S. Bajar, D. Pant, Z. Ud, Ethanol from lignocellulosic biomass: An in-depth analysis of pre-treatment methods, fermentation approaches and detoxification processes, J. Environ. Chem. Eng. 9 (2021) 105798, https://doi.org/10.1016/j.jece.2021.105798.

[88] A. Rao, M. Sathiavelu, Genetic engineering tolerance, BioButanol Prod. (2016), https://doi.org/10.1590/1678-4324-2016150612.

[89] M. Wang, L. Fan, T. Tan, RSC advances, RSC Adv. 4 (2014) 57791–57798, https://doi.org/10.1039/C4RA09016K.

[90] J. Huang, Y. Du, T. Bao, M. Lin, J. Wang, S. Yang, Bioresource Technology Production of n -butanol from cassava bagasse hydrolysate by engineered Clostridium tyrobutyricum overexpressing adh E2: kinetics and cost analysis, Bioresour. Technol. 292 (2019) 121969, https://doi.org/10.1016/j.biortech.2019.121969.

[91] S. Riaz, S. Mazhar, S. Hussain, Q. Syed, N. Abbas, Y. Saleem, Biobutanol production from sustainable biomass process of anaerobic ABE fermentation for industrial applications, Arch. Microbiol. 204 (2022) 1–9, https://doi.org/10.1007/s00203-022-03284-z.

[92] P. Andr, J.G. Teleken, T. Ricardo, W. Meier, Two-Stage anaerobic digestion in agroindustrial waste treatment: a review 281 (2021), https://doi.org/10.1016/j.jenvman.2020.111854.

[93] S. O-thong, W. Suksong, K. Promnuan, ScienceDirect Two-stage thermophilic fermentation and mesophilic methanogenic process for biohythane production from palm oil mill effluent with methanogenic effluent recirculation for pH control, Int. J. Hydrog. Energy 41 (2016) 21702–21712, https://doi.org/10.1016/j.ijhydene.2016.07.095.

[94] L. Rodrigues, G. Lovato, D. Rodrigues, L. Silva, Anaerobic digestion of vinasse in fluidized bed reactors: process robustness between two-stage thermophilic-thermophilic and thermophilic-mesophilic systems 314 (2021), https://doi.org/10.1016/j.jclepro.2021.128066.

[95] J. Banerjee, R. Singh, R. Vijayaraghavan, D. Macfarlane, A.F. Patti, A. Arora, Bioactives from fruit processing wastes: green approaches to valuable chemicals, Food Chem. 225 (2017) 10–22, https://doi.org/10.1016/j.foodchem.2016.12.093.

[96] H. Zabed, J.N. Sahu, A. Suely, A.N. Boyce, G. Faruq, Bioethanol production from renewable sources: current perspectives and technological progress, Renew. Sustain. Energy Rev. 71 (2017) 475–501, https://doi.org/10.1016/j.rser.2016.12.076.

[97] X. Chen, M. Khanna, E ff ect of corn ethanol production on conservation reserve program acres in the US, Appl. Energy 225 (2018) 124–134, https://doi.org/10.1016/j.apenergy.2018.04.104.

[98] G. Mugnai, L. Borruso, T. Mimmo, S. Cesco, V. Luongo, L. Frunzo, M. Fabbricino, F. Pirozzi, F. Cappitelli, F. Villa, Bioresource technology dynamics of bacterial communities and substrate conversion during olive-mill waste dark fermentation: prediction of the metabolic routes for hydrogen production, Bioresour. Technol. 319 (2021) 124157, https://doi.org/10.1016/j.biortech.2020.124157.

[99] V. Luongo, G. Policastro, A. Ghimire, F. Pirozzi, M. Fabbricino, Repeated-Batch Ferment. Cheese Whey Semi-Contin. Lact. Acid. Prod. Using Mixed Cult. Uncontrolled pH (2019) 1–12.

[100] G. Policastro, R. Lamboglia, M. Fabbricino, Enhancing Dark Fermentative Hydrogen Production from Problematic Substrates via the Co-Fermentation Strategy, (2022).

[101] A. Ghimire, L. Frunzo, F. Pirozzi, E. Trably, R. Escudie, P.N.L. Lens, G. Esposito, A review on dark fermentative biohydrogen production from organic biomass: process parameters and use of by-products, Appl. Energy 144 (2015) 73–95, https://doi.org/10.1016/j.apenergy.2015.01.045.

[102] U. De Corato, I. De Bari, E. Viola, M. Pugliese, Assessing the main opportunities of integrated biore fi ning from agro- bioenergy co / by-products and agroindustrial residues into high-value added products associated to some emerging markets: a review, Renew. Sustain. Energy Rev. 88 (2018) 326–346, https://doi.org/10.1016/j.rser.2018.02.041.

[103] G.De Guido, S. Moioli, M. Gilardi, F. Giudici, L.A. Pellegrini, Downstream processing of butanol produced by fermentation, Thermodyn. Meas. Model. 92 (2022) 625–630, https://doi.org/10.3303/CET2292105.

[104] The bioplastic market - Italy, Mark. Overv. Defn. Present. (2024). ⟨https://www.businesscoot.com/en/study/the-bioplastic-market-italy⟩.

[105] Q. Anh, E. Jin, D. Lee, H. Bae, Bioresource Technology Development of an advanced integrative process to create valuable biosugars including manno-oligosaccharides and mannose from spent co ff ee grounds, Bioresour. Technol. 272 (2019) 209–216, https://doi.org/10.1016/j.biortech.2018.10.018.

[106] L. Zhang, X. Li, Q. Yong, S. Yang, J. Ouyang, S. Yu, Simultaneous saccharification and fermentation of xylo -oligosaccharides manufacturing waste residue for l -lactic acid production by Rhizopus oryzae, Biochem. Eng. J. 94 (2015) 92–99, https://doi.org/10.1016/j.bej.2014.11.020.

[107] J. Li, J. Sun, B. Wu, B. He, Bioresource Technology Combined utilization of nutrients and sugar derived from wheat bran for D -Lactate fermentation by Sporolactobacillus inulinus YBS1-5, Bioresour. Technol. 229 (2017) 33–38, https://doi.org/10.1016/j.biortech.2016.12.101.

[108] F. Demichelis, S. Fiore, D. Pleissner, J. Venus, Technical and economic assessment of food waste valorization through a biorefinery chain, Renew. Sustain. Energy Rev. 94 (2018) 38–48, https://doi.org/10.1016/j.rser.2018.05.064.

[109] K.Y. Sen, S. Baidurah, Renewable biomass feedstocks for production of sustainable biodegradable polymer, Curr. Opin. Green. Sustain. Chem. 27 (2021) 100412, https://doi.org/10.1016/j.cogsc.2020.100412.

[110] A. Aramvash, Z.A. Shahabi, S.D. Aghjeh, M.D. Ghafari, Statistical physical and nutrient optimization of bioplastic polyhydroxybutyrate production by Cupriavidus necator, Int. J. Environ. Sci. Technol. (2015) 2307–2316, https://doi.org/10.1007/s13762-015-0768-3.

[111] J.S. Yaradoddi, N.R. Banapurmath, S.V. Ganachari, M.E.M. Soudagar, N. M. Mubarak, S. Hallad, S. Hugar, H. Fayaz, Biodegradable carboxymethyl cellulose based material for sustainable packaging application, Sci. Rep. 10 (2020) 1–13, https://doi.org/10.1038/s41598-020-78912-z.

[112] G. Pesante, N. Frison, Bioresource technology reports recovery of bio-based products from PHA-rich biomass obtained from biowaste: a review, Bioresour. Technol. Rep. 21 (2023) 101345, https://doi.org/10.1016/j.biteb.2023.101345.

[113] S. Jayarathna, M. Andersson, R. Andersson, Recent advances in starch-based blends and composites for bioplastics applications, Polymers 14 (2022) 1–24, https://doi.org/10.3390/polym14214557.

[114] A. Visco, C. Scolaro, M. Facchin, S. Brahimi, H. Belhamdi, V. Gatto, V. Beghetto, Agri-Food Wastes for Bioplastics: European Prospective on Possible Applications in Their Second Life for a Circular Economy, (2022).

[115] S.H. Kee, J.B.V. Chiongson, J.P. Saludes, S. Vigneswari, S. Ramakrishna, K. Bhubalan, Bioconversion of agro-industry sourced biowaste into biomaterials via microbial factories – a viable domain of circular economy, Environ. Pollut. 271 (2021) 116311, https://doi.org/10.1016/j.envpol.2020.116311.

[116] S. Pilafidis, P. Diamantopoulou, K. Gkatzionis, D. Sarris, Valorization of agro-industrial wastes and residues through the production of bioactive compounds by macrofungi in liquid state cultures: growing circular economy, Appl. Sci. 12 (2022), https://doi.org/10.3390/app122211426.

[117] M.G. Roth, N.M. Westrick, T.T. Baldwin, Fungal biotechnology: from yesterday to tomorrow, Front. Fungal Biol. 4 (2023) 1–11, https://doi.org/10.3389/ffunb.2023.1135263.

[118] T. Kleekayai, W. Suntornsuk, Production and characterization of chitosan obtained from Rhizopus oryzae grown on potato chip processing waste, World J. Microbiol. Biotechnol. 27 (2011) 1145–1154, https://doi.org/10.1007/s11274-010-0561-x.

[119] K.D. Hyde, J. Xu, S. Rapior, R. Jeewon, S. Lumyong, A.G.T. Niego, P. D. Abeywickrama, J.V.S. Aluthmuhandiram, R.S. Brahamanage, S. Brooks,

A. Chaiyasen, K.W.T. Chethana, P. Chomnunti, C. Chepkirui, B. Chuankid, N.I. de Silva, M. Doilom, C. Faulds, E. Gentekaki, V. Gopalan, P. Kakumyan, D. Harishchandra, H. Hemachandran, S. Hongsanan, A. Karunarathna, S. C. Karunarathna, S. Khan, J. Kumla, R.S. Jayawardena, J.K. Liu, N. Liu, T. Luangharn, A.P.G. Macabeo, D.S. Marasinghe, D. Meeks, P.E. Mortimer, P. Mueller, S. Nadir, K.N. Nataraja, S. Nontachaiyapoom, M. O'Brien, W. Penkhrue, C. Phukhamsakda, U.S. Ramanan, A.R. Rathnayaka, R.B. Sadaba, B. Sandargo, B.C. Samarakoon, D.S. Tennakoon, R. Siva, W. Sriprom, T. S. Suryanarayanan, K. Sujarit, N. Suwannarach, T. Suwunwong, B. Thongbai, N. Thongklang, D. Wei, S.N. Wijesinghe, J. Winiski, J. Yan, E. Yasanthika, M. Stadler, The amazing potential of fungi: 50 ways we can exploit fungi industrially, Fungal Divers 97 (2019), https://doi.org/10.1007/s13225-019-00430-9.

[120] R. Majumder, S. Miatur, A. Saha, S. Hossain, Mycoprotein: production and nutritional aspects: a review, Sustain. Food Technol. 2 (2024) 81–91, https://doi.org/10.1039/D3FB00169E.

[121] IPIFF, 2024, Guide on good hygiene practices for European Union (EU) producers of insects as food and feed, 2024..

[122] S. Smetana, M. Palanisamy, A. Mathys, V. Heinz, Sustainability of insect use for feed and food: life cycle assessment perspective, J. Clean. Prod. 137 (2016) 741–751, https://doi.org/10.1016/j.jclepro.2016.07.148.

[123] L. Delgado, C. Garino, F.J. Moreno, J. Zagon, H. Broll, Sustainable food systems: EU regulatory framework and contribution of insects to the farm-to-fork strategy, Food Rev. Int. 39 (2023) 6955–6976, https://doi.org/10.1080/87559129.2022.2130354.

[124] C. Zi-zhe, Y. De-po, W. Sheng-qing, W. Yong, M.J.T. Reaney, Z. Zhi-min, Z. Long-ping, S. Guo, N. Yi, Z. Dong, N. Hui-ran, Y. Wen-zhe, Conversion of poultry manure to biodiesel, a practical method of producing fatty acid methyl esters via housefly (Musca domestica L.) larval lipid, Fuel 210 (2017) 463–471, https://doi.org/10.1016/j.fuel.2017.08.109.

[125] H.A.A. Khan, Long-term impact of rearing substrates on susceptibility to insecticides and metabolic enzyme activities in the house fly Musca domestica, Parasitol. Res. 123 (2024), https://doi.org/10.1007/s00436-024-08180-7.

[126] E. Harsanyi, C. Juhasz, E. Kovacs, L. Huzsvai, R. Pinter, G. Fekete, Z. Varga, L. Aleksza, C. Gyuricza, Insects, Eval. Org. Wastes Substr. (2020).

[127] T.H. Li, P.F. Che, C.R. Zhang, B. Zhang, A. Ali, L.S. Zang, Recycling of spent mushroom substrate: utilization as feed material for the larvae of the yellow mealworm Tenebrio molitor (coleoptera: Tenebrionidae), PLoS One 15 (2020) 1–12, https://doi.org/10.1371/journal.pone.0237259.

[128] N. Kröncke, R. Benning, Self-selection of feeding substrates by tenebrio molitor larvae of different ages to determine optimal macronutrient intake and the influence on larval growth and protein content, Insects 13 (2022), https://doi.org/10.3390/insects13070657.

[129] F. Cominelli, M.C. Reguzzi, R. Nicoli Aldini, E. Mazzoni, Insect pest susceptibility of grains and seeds recently introduced to the Italian market: an experimental evaluation, J. Stored Prod. Res. 89 (2020) 101691, https://doi.org/10.1016/j.jspr.2020.101691.

[130] S. Zulkifli, A. Jayanegara, B. Pramudya, M.R. Fahmi, M. Rahmadani, Alleviation of selected environmental waste through biodegradation by black soldier fly (Hermetia illucens) larvae: a meta-analysis, Recycling 8 (2023), https://doi.org/10.3390/recycling8060083.

[131] M.F. Pazmiño, A.G. Del Hierro, F.J. Flores, Genetic diversity and organic waste degrading capacity of Hermetia illucens from the evergreen forest of the Equatorial Choco lowland, PeerJ 11 (2023) 1–21, https://doi.org/10.7717/peerj.14798.

[132] H. Wang, K.U. Rehman, X. Liu, Q. Yang, L. Zheng, W. Li, M. Cai, Q. Li, J. Zhang, Z. Yu, Insect biorefinery: A green approach for conversion of crop residues into biodiesel and protein, Biotechnol. Biofuels 10 (2017) 1–13, https://doi.org/10.1186/s13068-017-0986-7.

[133] M. Mikhailova, K. Zolotarev, V. Nakhod, T. Farafonova, A. Mikhailov, Nutritional value of black solder fly (Hermetia illucens) eggs and larvae reared on fermented milk industry waste as an ingredient of fish feed, E3S Web Conf. 363 (2022), https://doi.org/10.1051/e3sconf/202236303017.

[134] K. Magee, J. Halstead, R. Small, I. Young, Valorisation of organicwaste by-products using black soldier fly (Hermetia illucens) as a bio-convertor, Sustain 13 (2021) 1–17, https://doi.org/10.3390/su13158345.

[135] K.M. Eggink, Modif. Nutr. Compos. Black Soldier Fly. Hermetia illucens Forfish Feed Appl. 29 (2023).

[136] Z. Liu, M. Minor, P.C.H. Morel, A.J. Najar-Rodriguez, Bioconversion of three organic wastes by black soldier fly (Diptera: Stratiomyidae) larvae, Environ. Entomol. 47 (2018) 1609–1617, https://doi.org/10.1093/ee/nvy141.

[137] Y.S. Wang, M. Shelomi, Review of black soldier fly (Hermetia illucens) as animal feed and human food, Foods 6 (2017), https://doi.org/10.3390/foods6100091.

[138] C.Y. Wong, S.S. Rosli, Y. Uemura, Y.C. Ho, A. Leejeerajumnean, W. Kiatkittipong, C.K. Cheng, M.K. Lam, J.W. Lim, Potential protein and biodiesel sources from black soldier fly larvae: insights of larval harvesting instar and fermented feeding medium, Energies 12 (2019), https://doi.org/10.3390/en12081570.

[139] S.W. Management, R. Recovery, Compr. Assess. Thermochem. Process. (2023).

[140] EPA, United States Environmental Protection Agency, Compost. Benefits (2024). ⟨https://www.epa.gov/sustainable-management-food/composting#:~:text=and⟩ community composting.-,Benefits of Composting,materials and keeps them local.

[141] M. Kumar, S. Sarsaiya, S. Wainaina, K. Rajendran, S. Kumar, T. Liu, Y. Duan, A. Jain, R. Sindhu, Techno-economics and life-cycle assessment of biological and thermochemical treatment of bio-waste, Renew. Sustain. Energy Rev. 144 (2021) 110837, https://doi.org/10.1016/j.rser.2021.110837.

[142] D. Bolzonella, F. Fatone, M. Gottardo, N. Frison, Nutrients recovery from anaerobic digestate of agro-waste: Techno-economic assessment of full scale applications, J. Environ. Manag. 216 (2018) 111–119, https://doi.org/10.1016/J.JENVMAN.2017.08.026.

[143] N. Mahendrasinh Kosamia, M. Samavi, K. Piok, S. Kumar Rakshit, Perspectives for scale up of biorefineries using biochemical conversion pathways: technology status, techno-economic, and sustainable approaches, Fuel 324 (2022) 124532, https://doi.org/10.1016/j.fuel.2022.124532.

[144] V. Ashokkumar, G. Flora, R. Venkatkarthick, K. SenthilKannan, C. Kuppam, G. Mary Stephy, H. Kamyab, W.-H. Chen, J. Thomas, C. Ngamcharussrivichai, Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: emerging circular bioeconomy perspective, Fuel 324 (2022) 124313, https://doi.org/10.1016/j.fuel.2022.124313.

[145] S.T. Tan, W.S. Ho, H. Hashim, C.T. Lee, M.R. Taib, C.S. Ho, Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia, Energy Convers. Manag. 102 (2015) 111–120, https://doi.org/10.1016/j.enconman.2015.02.010.

[146] L.R. Jarboe, Z. Wen, D. Choi, R.C. Brown, Hybrid thermochemical processing: Fermentation of pyrolysis-derived bio-oil, Appl. Microbiol. Biotechnol. 91 (2011) 1519–1523, https://doi.org/10.1007/s00253-011-3495-9.

[147] A. Galvagno, M. Prestipino, G. Zafarana, V. Chiodo, Analysis of an integrated agro-waste gasification and 120 kW SOFC CHP system: modeling and experimental investigation, Energy Procedia 101 (2016) 528–535, https://doi.org/10.1016/j.egypro.2016.11.067.

[148] F. Jamil, M. Hussain Muhammad, M. Hussain, P. Akhter, A. Sarwer, A. Inayat, K. Johari, N. Shezad, S. Hoon Lee, Y.-K. Park, Life cycle assessment with the transition from lignocellulose- to microalgae-based biofuels: a review, J. Ind. Eng. Chem. (2023), https://doi.org/10.1016/j.jiec.2023.12.011.

[149] S.Y. Leong, S.R.M. Kutty, C.K. Tan, L.H. Tey, Comparative study on the effect of organic waste on lauric acid produced by Hermetia illucens larvae via bioconversion, J. Eng. Sci. Technol. 10 (2015) 52–63.

[150] H. Sun, Z. Luo, S. Li, S. Xue, Q. Zhou, T. Wei, L. Du, Comparative life cycle assessment (LCA) of biofuel production via corn stover: fermentation to ethanol, pyrolysis to bio - oil, and gasification to jet fuel, Biomass-.-. Convers. Biorefinery (2023) 12809–12821, https://doi.org/10.1007/s13399-021-02054-z.

[151] Y.Y.& G.S.J. Homa Hosseinzadeh-Bandbafha, Meisam Tabatabaei, Mortaza Aghbashlo, Anh Tuan Hoang, Life Cycle Analysis for Biodiesel Production from Oleaginous Fungi, Springer International Publishing, 2020.