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From urban trash to city cash: Technologies for sustainable development of cities through the valorisation of urban organic waste in Europe

Jessica Frigerio [a,1], Stefano Bertacchi [a,1], Sara Mecca [b,1], Stefania Digiovanni [a,1], Tania Molteni [c], Valeria Mapelli [a], Luca Beverina [b], Marina Lotti [a], Edoardo Croci [c], Paola Branduardi [a], Massimo Labra [a,*]

[a] Department of Biotechnology and Biosciences, University of Milano-Bicocca, Piazza della Scienza, 3, 20126 Milan, Italy
[b] Department of Materials Science, University of Milano-Bicocca, Via R. Cozzi, 55, I-20125 Milan, Italy
[c] GREEN (Centre for Research on Geography, Resources, Environment, Energy and Networks), Bocconi University, Via Guglielmo Roentgen, 1, 20136 Milan, Italy

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ABSTRACT

In recent years, the rising awareness towards sustainability led to a joint multilevel effort among policy makers, stakeholders, citizens and scientific researchers to decrease the urban impact on the environment. In this context, the organic fraction of municipal solid waste (OFMSW) is definitely relevant because of its impressive amount, but also for the issues related to traditional disposal processes (*i.e.* landfilling). For this reason, several physical–chemical and biotechnological treatments have been implemented to solve the problem of waste storage, while producing new value. In addition, new technologies have been studied to fully exploit the potential of OFSMW, especially the material which could be easily sorted. This review aims to offer a comprehensive overview of the well-established and developing technologies for the valorisation of OFMSW, with an analysis of their benefits and drawbacks, in addition to interesting insights into the good practices already implemented in the European scenario.

Introduction

Within the European Union, approximately 118 to 138 million tons of bio-waste are produced each year, with around two-third originating from urban areas (Interreg Europe, 2021). According to Directive (EU) 2018/851 of the European Parliament and of the Council (amending Waste Framework Directive 2008/98/EC – article 1(3)(b)), bio-waste is defined as “biodegradable waste from gardens, parks, households, offices, restaurants, wholesalers, canteens, caterers, retail premises, as well as similar waste from food processing plants” in the territory (European Union, 2008). Bio-waste accounts on average for 30–40 % of municipal solid waste (identified as “organic fraction of municipal solid waste” – OFMSW), although this percentage may vary among Member States, ranging from 18 % to 60 %. Consequently, the average European citizen generates approximately 200 kg of urban bio-waste annually: these values highlight the critical role of OFMSW management and its impact in urban sustainability (European Commission, 2020). Existing urban bio-waste management systems in Europe have relied on landfilling (accounting for 40 % of bio-waste disposal) and incineration, with composting and anaerobic digestion only recently gaining attention. The first two options currently fail to extract the full resource potential contained therein, whilst exacerbating economic, environmental and social issues such as odors, greenhouse gas emissions in urban environment, and inefficient use of lands that do not generate profits. The other more recent alternatives still do not fully maximize the opportunities presented by bio-waste. One of the prominent challenges in bio-waste management is the integration of a valorisation system within urban environments aiming to recover products with market value that can offset the overall cost of bio-waste valorisation (European Compost Network ECN, 2022).

The recent revisions in European Union’s waste legislation, aligned with the EU’s circular economy strategy (European Commission, 2020; European Union, 2020), have introduced targets and provisions to promote both the prevention and the sustainable management of bio-waste. Achieving the EU’s target of recycling 65 % of urban waste by 2035 heavily relies on the recycling of bio-waste, as also is widely

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* Corresponding author.
E-mail address: massimo.labra@unimib.it (M. Labra).
[1] These authors contributed equally to the work.

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stressed in the European Green Deal (European Union, 2019), which has brought forth investments in areas such as anaerobic digestion and other treatments to foster demand and robust markets for organic nutrients and biomethane while encouraging low-carbon economy. In the policy framework fostered by Green Deal strategies, bio-waste becomes a crucial driver for circular resource recovery, contributing to:

- soil restoration and urban greening initiatives through compost-based soil improvers readily employable in the urban areas;
- sustainable agriculture via organic fertilizer and bio-based nutrients that go on the citizen tables;
- renewable energy production through biogas generation;
- climate mitigation by reducing landfill-related uncontrolled methane emissions.

In order to develop effective, coordinated and sustainable systems for the reuse and recycling of urban bio-waste, it is necessary to adhere and leverage political strategies that fall within the paradigm of urban ecological transition approach. This must be supported by i) solid, advanced and scalable technologies, adaptable to different matrices and capable of transforming biomass into products (including energy) following cascading principles (*i.e.* the sequential and consecutive use of resources (Campbell-Johnston et al., 2020)); ii) financial and economic strategies capable of promoting processes of circular (bio)economy and industrial contamination and symbiosis, such as suggested/strategic/market-driven investments following a precise business plan or virtuous examples; iii) operational best practices, such as identification and deepening of pilot projects and case studies demonstrating to stakeholders, institutions and citizens successful bio-waste valorization models that can be adapted across diverse urban contexts; iv) analysis of the actual urban context, with a particular attention to identification, deepening and overcoming of all the barriers to the adoption of an urban ecological approach, at social (such as lack of awareness and education – (Bagagiolo et al., 2022)), economic and institutional level, in order to start from the support of local-level initiatives and then to reach the institutions.

This review aims to explore and analyse strategies for urban bio-waste valorization through these principal key points: i) mapping the principal categories of urban biomasses, their composition and their origin;

ii) evaluating scientific and technological advancements that enable sustainable and economically viable valorization processes; iii) identifying virtuous examples and good practices adaptable to different urban contexts both in Europe and globally.

By addressing these aspects, this review seeks to highlight how urban bio-waste valorization can be a pivotal tool for sustainable urban development, aligning with the EU's green transition goals while creating economic, environmental and social benefits.

Urban biomass: Characteristics and availability

As aforementioned, to deconstruct ambiguity about what can be considered bio-waste, Directive (EU) 2018/851 reports the definition very clearly. Starting from this definition, bio-waste can be divided into three main categories (see Fig. 1).

Food-derived waste. This category includes organic waste from kitchens (private and public), canteens, markets, and domestic composting. Globally, the world generates 1.3 billion tons of food waste annually, representing roughly one-third of all food produced (FAO, 2013). All the actions against the waste of still edible food are out of the scope of this review: we will refer only to non-edible food waste streams. In Europe, food waste constitutes approximately 60 % of bio-waste. More specifically, 61 % of food waste come from households, 26 % from food service and 13 % from retail (United Nations Environment Programme, 2021). In the EU, approximately 57 million tonnes of food are discarded each year, equating to 127 kg per inhabitant (Eurostat, 2022). This bio-waste is a complex and heterogeneous mixture of plant- and animal-derived components (Alibardi & Cossu, 2015). The composition is thus extremely variable upon sources, geographical context and seasons. Food-waste is generally characterized by a high moisture content (up to 80 %) affecting storage volume and shelf-life (Banks et al., 2018), various types of carbohydrates (mainly starch and cellulose), sugars, lipids, proteins (Paritosh et al., 2017), lignin, and also bioactive compounds, like long-chain polyunsaturated fatty acids, vitamins, carotenoids, peptides, and polyphenols (Georganas et al., 2020; Pagliaccia et al., 2019).

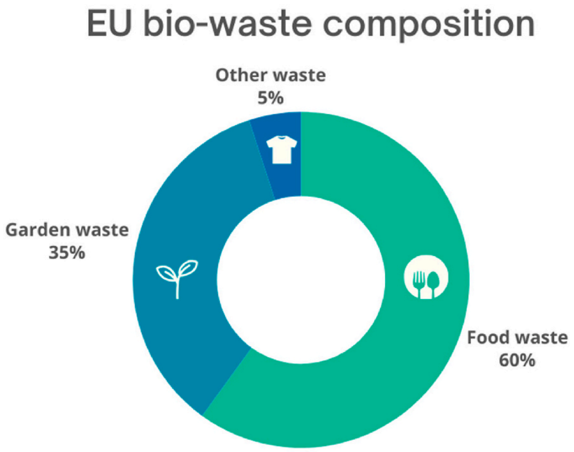

Fig. 1. Distribution by categories of urban organic biomass (Eurostat, 2022).

Literature results highlight bio-waste generation across EU countries but lack data on geographical and seasonal compositional variations. Key insights (Eurostat, 2024) include:

- Geographical Variations: Cyprus, Belgium, and Denmark have the highest *per capita* food waste, while Slovenia, Croatia, and Sweden have the lowest. The amount of edible food waste doubles from rural to urban areas. Fruits (27 %), vegetables (20 %), and cereals (13 %) make up most of the waste EU-wide, but regional differences have still to be deepened.
- Seasonal Variations: No direct data on seasonal shifts, except for preliminary studies that report that urban bio-waste remains relatively stable throughout the year, whilst family house bio-waste fluctuates significantly due to the presence of seasonal garden waste (Hanc et al., 2011).
- Data Limitations: Reports focus on sectoral splits rather than regional or seasonal composition, and EU measurement standards prioritize mass over content analysis.

This analysis suggests that more detailed regional studies would be needed for deeper insights. The best option should be the development of biorefineries based on the local feedstock availability, for example through the use of a decision support tool (De Buck et al., 2022). Improving these tools with variability data could help developing tailored processes depending on season and geographical area.

Garden waste: This refers to bio-waste arising from the maintenance of gardens, public and private parks, and urban green areas. Usually this consists of several species and types of woody biomass and green portion of plant (leaves, stems, flowers). It is estimated that this percentage is growing in Europe and exceeds 35 % of the total waste. Garden waste is characterized by a relatively significant lignocellulose composition, with an average content of 27 % to 57 % cellulose, 11 % to 55 % hemicellulose, and 3 % to 22 % lignin, based on dry matter (Liu et al., 2023). Assessments in different countries have demonstrated the potential of this underutilized urban green biomass (especially wood) as a resource to produce energy; moreover, the growing urban forestation activities could support the development of new technologies and a dedicated urban supply chain to the recycling, reuse and upcycling of these biomasses (Biocca et al., 2022).

Other: This category is composed of a wide variety of bio-waste, which may be produced in different urban contexts and practices. The substantial difference compared to the previous categories is that in some cases they are purer resources and less heterogeneous compared to other bio-waste but at the same time they do not have adequate logistics for collection and transport strategies. As an example, in this category we find human hair, which is collected in high quantities from hairdressers and is commonly disposed of. In Europe, an estimated 72 million kg of human hair waste is generated; its fundamental constituent is keratin (Mondal et al., 2020; Mukherjee et al., 2023), which has been used as a nutrient in agricultural land (Zheljazkov, 2005). Therefore, efficient sorting and collection of human hair and pet fur (Waliczek et al., 2021) has the potential to generate a valuable waste valorisation chain.

Textile waste is also totally or partially deriving from biomasses (the remaining part is composed of synthetic polymeric fibres). Globally, 92 million tons of textile waste is produced each year and in Europe approximately 11 kg of textile waste is generated on average per person every year. Only half of the used clothing is collected for reuse or recycling with only approximately 1 % reintroduced into new clothes. Many of the collected clothes end up being exported, and ultimately, a majority of textiles (87 %) are either incinerated or disposed of in landfills (Zero Waste Europe, 2021).

Urban regeneration projects must implement strategic actions aimed at optimizing the collection and enhancing the value of bio-waste that can be used, starting from the sorting of the different types of biomass-derived waste and reducing the contamination from non-organic waste, also by developing pre-cleaning processes, optical-sorting systems, and supporting citizens in collection.

For example the recent spread of plastic products labelled 'compostable' and 'biodegradable' already promoted urban collection of organic waste in virtuous cities like Milano (Italy) (Collacott, 2022). Nevertheless, these materials might pose confusion among consumers and even increase the contamination risk of bio-waste with non-compostable plastics if not well received by citizens, highlighting the need for clear communication strategies.

The choice and development of the best transformation process require analysing the exact composition of the bio-waste. Technological innovation allows us to identify procedures aimed at valorising specific compounds starting from macromolecular aggregates such as plant fibres up to small molecules. Generally, bio-waste valorisation processes can follow chemical-physical, biotechnological treatments or a combination thereof.

Consolidated processes for the valorisation of bio-waste: composting and anaerobic digestion

Composting and anaerobic digestion (AD) are currently the two most widely applied treatment techniques for the valorisation of bio-waste. While both processes yield solid end products such as compost (used as fertilizer, soil improvers, growing media constituents), or digestate (utilized again as organic fertilizer or soil improver), anaerobic digestion's main product is biogas. In Europe, composting dominates bio-waste treatment with 42 tons per year, whereas anaerobic digestion disposes 29 tons per year of bio-waste (European Compost Network ECN, 2022). European household bio-waste represents 73 % of the total composted material, whereas for AD the share of bio-waste is 46 %. Nowadays, in Europe there are approximately 5,800 bio-waste treatment facilities, with 66 % being composting and 34 % anaerobic digestion plants. Among these, 88 % of composting facilities and 48 % of anaerobic digestion plants exclusively handle bio-waste (European Compost Network ECN, 2022).

Composting is an aerobic process where native microbiota (mainly bacteria, fungi, and protozoa, but also archaea) decompose bio-waste. The humus-like product, namely compost, is the fertilizer of choice in many cases with parameters such as stability and maturity being those to be assessed on the final product (Azim et al., 2018; Venkata Mohan et al., 2020). Due to the use in agriculture, compost can be considered a direct material restitution to the countryside, where the food originated. This of course creates virtuous circles, that might fit directly into city boundaries when considering compost use in urban agriculture, creating a closed-loop environment (Dsouza et al., 2021; Salomon et al., 2020; Salomon & Cavagnaro, 2022; Ulm et al., 2019).

Compost yield may vary from different processes with specific peculiarities, but generally it is assumed that its value in composting is 40–44 % w/w of bio-waste (European Commission, 2001; Pavlas et al., 2020) leaving a certain amount of biomass still to be disposed of. In addition, a critical point from the technical perspective is the heterogeneous nature of bio-waste, in terms of both composition and seasonality. This can impair the consistency of the process itself, since the biomass is the feedstock for microbial growth, resulting in changing parameters (Hanc et al., 2017). Nevertheless, the amount of greenhouse gasses emission of composting varies when using different biomasses, namely OFMSW, garden waste, manure and sludge (Nordahl et al., 2023). For example, composting OFMSW releases on average 8.79×10^{-4} kg of CH_4, 6.80×10^{-5} kg of N_2O, and 5.63×10^{-2} kg of CO_2 per kg of wet feedstock (Nordahl et al., 2023).

A hurdle from the social point of view is the fact that the integration of composting into the urban cycles needs the engagement of an active citizenry, especially when dealing with community composting (Pucherová et al., 2021). Nowadays, in many cities projects dedicated to decentralized community composting are spreading with the goal to provide local communities with compost to be used from urban agriculture to gardening (Plana González-Sierra et al., 2019). For example, the metropolitan city of Lyon (France) has been considered as a case study for different scenarios where decentralized biorefineries networks could work (Angouria-Tsorochidou et al., 2022).

Anaerobic digestion is a process that involves several microbial species, mainly bacteria and archaea, able to transform organic matter into a mixture of carbon dioxide and methane (Harirchi et al., 2022). Biogas yield is assumed to be 100 Nm^3/t of bio-waste (European Commission, 2001; ISPRA, 2022; Pavlas et al., 2020). Biogas production via AD is generally obtained by four phases in sequence: hydrolysis of organic matter structure; acidogenesis for the synthesis of volatile fatty acids (VFAs) like propionate, butyrate, acetate; acetogenesis for the transformation of VFAs into acetate and finally the methanogenesis from acetate (Bertacchi, Ruusunen, et al., 2021; Harirchi et al., 2022). The main application of biogas (or the purified biomethane) is heat and electricity generation and represents a renewable alternative to natural gas (Abanades et al., 2022; Nevzorova & Karakaya, 2020; Venkata Mohan et al., 2020). For example, several Swedish municipalities deploy vehicles for public transport fuelled by biogas/biomethane, shaping sustainable markets for urban contexts, thanks to prioritization of fossil-free solutions, dedicated policies and a fruitful network of stakeholders (Gustafsson & Anderberg, 2023; Lundmark et al., 2021; Ottosson et al., 2020).

One of the main criticisms pertaining AD is the valorisation of the main side product, namely digestate, since its heterogeneous nature (liquid, solid, gaseous) and the dependency from the initial feedstock make the exploitation complex, despite the huge potential in terms of nutrient composition. The digestate is currently mainly used as fertilizer and as biomass for further gasification/pyrolysis; however, its use in microbial based processes is growing (Chozhavendhan et al., 2023; Wang & Lee, 2021). For example, the digestate can be used as a growth medium for microalgae to produce compounds of industrial relevance, such as biofuels or food additives (Magoni et al., 2022; Stiles et al., 2018). The digestate can also be recycled by composting, fostering the connection between AD and composting (Czekała et al., 2023). Therefore, the valorisation of digestate should be considered when developing an integrated biorefinery based on AD from urban biomass, to increase the appeal and circularity of such processes. Another issue related to AD that can be overcome through an increased awareness of citizens in waste separation is plastic contamination in OFMSW. This contamination is acknowledged to have detrimental effects on both composting and AD processes. Notably, recent studies have highlighted that microplastics (MPs), in particular, can significantly disrupt AD performance by interfering with microbial pathways, reducing methane yield. These findings underscore the importance of addressing non-compostable plastic contamination as a critical barrier to the development of resilient and efficient bioenergy systems (Ali et al., 2025).

New strategies for bio-waste valorisation

To implement the valorisation of bio-waste it is necessary to identify innovative strategies (or to optimize the existing ones) capable of developing products with high added value along with reducing processing costs. Investments encouraging the development of scientific and technological innovations are necessary in three most ways:

1) *Separate collection.* Nowadays urban bio-waste is a heterogeneous mixture with a largely variable composition, since the separation of specific components of urban bio-waste would be difficult to implement in households and the hospitality sector. This limits its potential employment in specific productive processes, where reproducibility and controlled conditions are essential. Thus, it is necessary to identify separate collection procedures and also conservation approaches for some bio-waste to be conveyed towards certain valorisation chains. To achieve this goal, municipalities can adopt several key strategies. Door-to-door collection, especially for food waste, helps reduce contamination and increase recycling rates. Extending this system to businesses like restaurants and markets ensures better waste management for items like coffee grounds and meat scraps. Sector-specific collection can further optimize efficiency, targeting businesses such as hair salons (for human hair), butcheries (for meat waste) and fisheries (for fish waste) (LIFE BIOBEST, 2023). Public awareness campaigns and clear guidelines encourage participation, while providing free compostable bags makes the process easier. To handle garden waste, designated drop-off points can help manage seasonal fluctuations. Pre-treatment methods like sorting, drying, or compacting improve waste quality and transport efficiency. Finally, partnering with facilities that turn bio-waste into compost, biofuels, or animal feed ensures proper valorization, creating a virtuous network and supporting a circular economy (Mission Zero Academy, 2021; Wanderley et al., 2022).

2) *Supply.* The second aspect to consider pertains to the volume and consistent supply over time. Many valorisation and transformation processes become economically viable only when handling substantial quantities, and when the input pipelines are consistently fed with materials for recycling. Achieving economic sustainability in bio-waste recycling processes hinges on efficiently managing not only the volume of waste materials but also adapting to variations in supply, which can be influenced by factors like seasonality and the available infrastructures for waste collection and aggregation.

3) *Urban biorefineries.* The development of biorefineries integrated in the local urban environment is fundamental to develop sustainable industrial processes able to produce new chemical or biological products with high commercial values (*e.g.* pharmaceutical compounds, foods). This kind of biorefineries valorise organic matter of different origin, by defining the most suitable processes to obtain specific products also considering the local demand and the principles of the bioeconomy (Satchatippavarn et al., 2016; Solarte-Toro & Alzate Cardona, 2021). The concept of physical proximity with the generation processes of primary biomass is an essential element to reduce the costs related to biomass shipping, storage and processing (Spatari et al., 2020), and to increase the economic appeal of the final products. In Europe, where the additional challenge will be to dimension the biorefinery to the maximum possible input of biomass, pilot studies of urban biorefineries based on local biomasses are strongly needed, as demonstrated by some funded project at local (BioUrbaNA) or transnational (URBIOFIN) level (BioUrbaNA, n.d.; URBIOFIN, n.d.).

Innovative chemical-physical processing technologies for bio-waste valorisation

Two main concepts can be considered when treating bio-waste with chemical-physical processes: the intrinsic degradation or the conservative upcycling. In the first case, the processes are intended to break down the complex bio-polymeric structures composing the substrates into simpler chemical species/platform chemicals useful to build value-added products; by contrast, in the conservative upcycling the macro-structures are maintained and treated to refine their structural intrinsic capability that could be directly employed again in new materials and compounds. Degradation methodologies encompass thermally induced scissions/reactions such as pyrolysis, combustion and gasification, and hydrothermal processes. On the other hand the conservative upcycling builds upon the extraction of value-added substances through both traditional and innovative greener methods and mild treatments developed to collect and directly reuse the structural macromolecules.

As shown in Fig. 2, new chemical-physical and biotechnological strategies have been studied in order to extract the full potential of the OFMSW. These strategies will be discussed in the following sections.

Waste breaking down by dry thermochemical processes

Thermal conversion is one of the most applied methods to treat bio-waste (Lohri et al., 2017). It can be performed either in the presence of oxygen (classic incineration, or gasification in oxygen limitation) or under inert or reductive atmosphere (pyrolysis). The latter processes are characterized by the controlled environment that favours specific chemical reactions and avoids complete oxidation. The pyrolytic process can be addressed differently depending on the working temperature range: torrefaction process (for temperatures below 350 °C) (Ciolkosz & Wallace, 2011; van der Stelt et al., 2011), carbonization (below 500 °C) or high temperature pyrolysis/gasification (around 750 °C) (Vakalis et al., 2017). Usually, input materials are dried to maximise the heating value. In fact, the presence of moisture induces high energy losses as every kg of water in biomass requires 2.26 MJ for vaporization (Lide, 2008). The process is compatible with almost every C-rich material, especially lignocellulose but also water sludges, with correspondingly different outputs (Ji et al., 2022). In general pyrolysis of biomass produces solid biochar, liquid (tar and oil) and non-condensable gases (also called syngas) with yields that depend on the operating conditions and feedstock properties (Sette et al., 2020). For example, the torrefaction output is mainly biochar (40–90 %), whilst for high temperature pyrolysis syngas is the principal outcome (90–100 %). Liquids can be obtained with intermediate conditions (20–55 %) (Spokas et al., 2012).

The yield of a specific target product is defined as the quantity of output over the dry input employed (Suliman et al., 2016). To increase oil or solid yield specifically, several parameters such as heating ratio, residence time, reaction pressure, vapour condensation rate can be tuned (Vamvuka, 2011). The obtained products are increasingly gaining attention; for the solid biochar many promising characteristics have been deeply analysed, such as its elemental content, its C-sequestration effect (Crombie et al., 2013), its porous distribution (Pituello et al., 2015) (for soil amendments, due to the presence of nitrogen), the solid fuel (Ortiz et al., 2020), catalytic (Shrestha et al., 2022) and adsorbing ability (Mauri et al., 2014). Liquid and gaseous products are involved in fuel applications as well (Vamvuka, 2011). Criticisms of these processes are evident; high energy input and pollutant gaseous losses require major further optimization. For the former, the most employed alternative is microwave heating, which is demonstrated to also increase product yield and selectivity, thanks to uniform and effective heating also without the necessity of catalysts (Budarin et al., 2015), whilst for

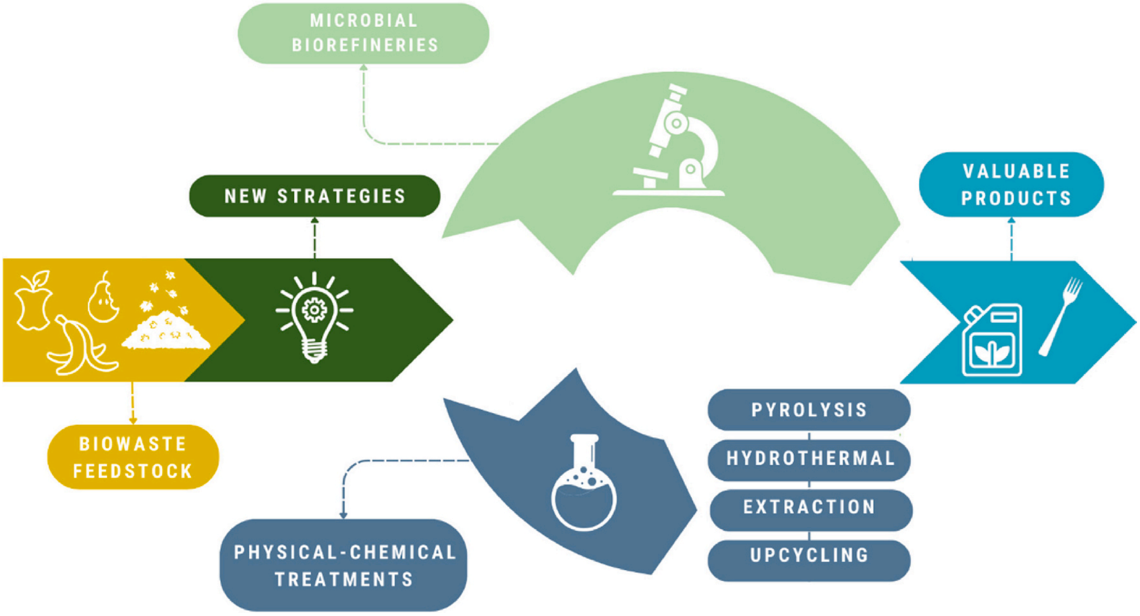

Fig. 2. graphical representation of possible strategies to valorise urban bio-waste in biorefineries. Microbial biorefineries and physical–chemical treatments are options that can be integrated in the same processes, to valorise the provided biomass with tailored solutions.

the pollutant gaseous losses a possibility is to return the non-condensable gasses to the pyrolysis reactor as a carrier gas (Kan et al., 2016). Thanks to technological improvements on reactor configurations and advanced processes (Vamvuka, 2011), the European Union countries already moved from feasibility studies (Ciolkosz & Wallace, 2011) to precompetitive development on pilot plants, such as BTG Bioliquids in the Netherlands (Pilots4U, 2024).

Waste breaking down by hydrothermal treatments

Hydrothermal (HT) treatments encompass all processes that take advantage of the use mainly of hot compressed water, either in sub- or supercritical conditions, or supercritical fluids (SCF) as processing media. A SCF is a material in a state above the critical temperature and critical pressure where gasses and liquids can coexist. The main advantage is that water acts as medium, but also as reactant and catalyst at the same time and for this reason can be considered an eco-friendly process, since it avoids the presence of organic solvents. Moreover, the substrates can be employed directly in the wet form, eliminating the energy-consuming step of drying, making it easy to operate and cost-effective (Sepúlveda et al., 2018). The extreme conditions favours the accessibility, depolymerization and breaking down of the biomass components into a solid residue (hydrochar), liquid (non-water soluble bio-oil and polar organic molecules, phenols, furfural and organic acids that can be employed as platform chemicals or new building blocks) and gasses, and there are numerous examples of their characterization reported in literature (Gao et al., 2012). Lignocellulosic materials are the main input of this process, whereas the output distribution strongly depends on both operating conditions and feedstock employed. HT liquefaction employs temperature between 250–374 °C and pressures between 5–22 MPa and is more directed towards bio-oil (Akhtar & Amin, 2011). On the other hand HT carbonization is performed below 250 °C and 5 MPa and finalized to hydrochar (Khan et al., 2021). For example, the hydrochar yield from HT carbonization can vary between 30 and 70 %: for a woody biomass is around 65 % with respect to 55 % obtained from municipal solid waste (Khan et al., 2021). A quantitative example of bio-oil yield, derived from HT liquefaction (HTL), is around 70 % (Çağlar & Demirbaş, 2001; Khan et al., 2021). It is worth noting that yield value is not an indicator of hydrochar quality (and this is true for every type of treatment), as can be for example higher heating value (HHV) for fuel applications.

This approach also has some technical problems. Despite the employment of lower temperatures with respect to pyrolytic processes (gasification stage takes place from 374 °C and not 750 °C, differently from dry pyrolysis), the energy consumption to reach the needed pressures remains elevated, especially if the water supercritical point has to be reached (Brunner, 2015). Despite all this, HTL has been already scaled up in some technological pilot plants in Germany, Italy and Finland (Buttmann, 2019; De Silva et al., 2023; Vikstedt, 2020).

Extractive processes

Bio-waste can contain a wide variety of biochemical and bioactive species: phenolic acids, flavonols, anthocyanins, pigments, carotenoids, pectin and essential oils are just some examples. In the previously reported techniques, these bioactive species are broken down along with the other macromolecules. Alternatively, these components can be extracted from the complex biomass matrix and employed as value-added products for food, pharmaceutical, and cosmetic industries. The type and amount of different phytochemical compounds vary widely depending on the input composition: the average percentage of each compound is reported in literature for almost every fruit and vegetable waste (Bisht et al., 2023). For each target compound (and waste), there is an indicated extraction technique: for example, methanol-based cold percolation extraction method has been demonstrated to be the most effective for terpenoids gathering in sweet orange peels (Thakur et al., 2020). The conventional extraction methods (both the industrially employed and the last century literature techniques) are room temperature or heated organic solvent extraction (*e.g.* soxhlet extraction) (Vella et al., 2018), hydrodistillation (Mahanta et al., 2020) and maceration (Krivokapić et al., 2021).

These techniques are simple and best-suited for small-scales despite that the extractive yield of specific target species is intrinsically limited (μg of product over g of input materials), due to their presence in low amounts in the biomass (Krivokapić et al., 2021). Furthermore, these techniques are time consuming, require large quantities of hazardous organic solvents (*e.g.* methanol) and thus are not environmentally friendly. As a consequence, starting from the last decade non-conventional or greener alternative techniques are emerging (Mena-García et al., 2019). They rely on improved efficiencies to reduce extraction period and thus energy use and employment of hazardous solvents. For example, toxic solvents can be substituted with eco-friendly and more efficient alternatives as ionic liquids (Martins et al., 2017), natural deep eutectic solvents (Abbott et al., 2004; Lobato-Rodríguez et al., 2023) or, in correlation with the previous paragraph, supercritical CO_2 (Bello et al., 2023; Raventós et al., 2002; Scaglia et al., 2020). Concurrently, the substrate can be treated with different electromagnetic processes (pulsed electric field – PEF, high voltage electric discharge – HVED, pulsed ohmic heating – POH), ultra-sounds (US) or micro-waves (MW). They easily damage cell membranes and favour penetration of medium and thus extraction of components (Barba et al., 2016).

Even if the majority of the reported processes are developed and show maximum efficiency when operated on a single specific substrate, this knowledge can be exploited to build a method for complex matrices such as OFMSW. Moreover, most works concerning the extraction of bioactive compounds from agri-food residues focus on the extraction process and discard the remaining solid. This by-product, rich in lignocellulosic-derived compounds, can be used to obtain fuels and energy using thermochemical treatments, such as the aforementioned pyrolysis and gasification (Barba et al., 2016; Sette et al., 2020), or further processed by enzymatic hydrolysis and fermentation (as described in 3.8), favoring synergies between different treatment processes and circular loops.

Conservative upcycling

The conservative upcycling involves minimum chemical and/or enzymatic processing of the biomasses, aiming at retaining the maximum possible carbon content in a high added value product. Biomasses rich in structural polysaccharides (*e.g.* vegetable and fruit skins) are particularly suitable for this approach. Processing is limited to drying and grinding, leading to a powder that upon minimal chemical/enzymatic digestion (mostly a room temperature partial hydrolysis) providing suitable reactive functionalities (*e.g.* carboxylic acids) can be blended with several biopolymers, in turn leading to polymer composites suitable for packaging and fabrics as well as additives for the construction industry and soil amendments (Andrew & Dhakal, 2022). The process is simple, easily scalable, eco-friendly and enables the valorisation of the maximum possible carbon content with negligible production of CO_2. The idea can be in principle applied to every lignocellulosic substrate and their mixture, with the outcome varying along with composition. The most promising results reported in literature are developed on different single-type substrates like orange peels, spinach stems, and carrot pomace (Perotto et al., 2018, 2020). All of them derive from different parts of the plants and the compatible response to the same treatment confirms the possibility to extend the protocol to other wastes, comprising complex mixed matrices. The process has been tested by employing different acids, improving the environmental impact (from trifluoroacetic acid (Bayer et al., 2014) to acetic acid (Merino et al., 2021)). Hydrolysis reaction leads to the deconstruction of plant cell structure, interfering with its supramolecular assembly, and partially hydrolysing the macrochains of the constituent polymers, releasing cellulose microcrystals and phytochemicals (Bayer et al., 2014). The obtained dispersions can be directly formulated and cast or centrifuged to recover the powder. In the first case, they reassemble into stand-alone, compact self-assembled composites, depending on the concentration of different species like starch and pectin, and can be optimized in their mechanical properties with addition of other eco-friendly plasticizers as well (Merino et al., 2021). Moreover, the output hydrolysed suspensions can be applied as coatings directly on fruit or other foodstuff surfaces. In the powder recovery case, treated material can be incorporated in hosts materials, such as cement for greener urban construction sector (Chen & Yang, 2023), or more often polymers (*e.g.* polylactic acid or polybutylene succinate (Nanni et al., 2021)) in various ways, such as extrusion (Momeni et al., 2021) and compression moulding, solvent casting or simply mixing (Torres et al., 2019) as a reinforcing agent or bio-fillers. In principle, such polymers can be obtained by microbial (natural or engineered) fermentation, even from residual biomasses. In the following pages additional examples will be featuring the production of the polymers polyhydroxyalkanoates (PHAs) from urban bio-wastes. The conservative upcycling is still an emerging trend, so no pilot plants have already been developed.

Microbial biorefineries based on bio-waste

Microorganisms are naturally able to transform organic and inorganic matter thanks to their ability to use different carbon and energy sources for their metabolism, their ability to withstand critical environmental conditions (extreme pH values, temperature, heterogeneity of substrates) and their high growth rate.

Considering the three categories of urban bio-waste, food residues and “green” leftovers are the most commonly handled by microbial processes, with AD and composting being prominent examples. Excluding grass and most kitchen residues, the presence of lignocellulosic biomass may occur, causing the involvement of pre-treatments to increase the accessibility to macromolecules. This in turn influences the overall process both in terms of deployment of saccharolytic enzymes and the choice of the microbial cell factories (*e.g.* bacterial, fungal) (Bertacchi, Jayaprakash, et al., 2021). The main goal is to dismantle the structure of the biomass, to release sugars, lipids and peptides then used by microbial cell factories as carbon and energy source, as well as feedstock for the synthesis of relevant compounds of industrial interest (Bertacchi, Jayaprakash, et al., 2021; Rosini et al., 2023).

It is very important to remark that the heterogeneous composition of bio-waste and its seasonality often hinder the development of a tailored microbial bioprocess based on microbial cell factories, while the use of a single-origin biomass provides a robust coherence to produce specific products. In general, residual biomasses such as bio-waste are classified as second generation ones, which compared to first generation ones – based on edible crops – is more compliant with cascading principles (IEA Bioenergy Task40, 2016), while facing hurdles in terms of efficiency and product yields. Below we report some examples of microbial processes dedicated to different classes of bio-waste which are also fundamental for producing valuable products for the urban context and needs. In addition to microbial processes, insect-mediated bioconversion of biomass is gaining increasing attention and has shown promising results at the laboratory scale (Bruno et al., 2025; Tepper et al., 2024).

Anyway, here we focus on three aspects of biotechnological processes for the valorisation of bio-waste: direct production of high-value molecules, production of polyfunctional molecular intermediates, and enzymatic approach to bio-waste valorisation.

Direct production of high-value molecules

As mentioned above, fertilizers and biomethane from composting and AD, respectively, are the main products obtained from microbial factories. However, from a circular economy point of view, fuels and energy are considered low-value products, while more and more interest is growing around the possibility of obtaining high-value products such as food ingredients and pharmaceuticals, as well as chemicals and polymers (Stegmann et al., 2020). The main limitation to producing high-value products from OFMSW is its heterogeneous and variable composition, which makes it difficult to standardize the industrial processes to obtain consistent results. For this reason, several studies have been carried out for the use of single types of waste that can be better characterized. Most of these studies analyse the feasibility of processes to obtain pigments and organic acids for food, cosmetics and pharmaceutical uses from bio-waste (Ben Rebah & Miled, 2013; Di Lorenzo et al., 2022; Petrik et al., 2014).

Production of biopolymers

Polyhydroxyalkanoates (PHAs) are a family of heterogeneous biodegradable and compostable polymers, with polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV) being the most common ones, naturally produced by different bacterial species. Overall, in 2022 PHAs represented roughly 4 % of the total bioplastics (bio-based and/or biodegradable) on the market (European Bioplastics, 2023).

Urban bio-waste can be used to produce these materials, despite yields appearing very low. It was suggested that to produce 1 kg of PHAs, cities like Barcelona (Spain), Lisbon (Portugal) and Copenhagen (Denmark) will need to deploy from 44 to 50 kg of food bio-waste assuming 100 % source separation (Andreasi Bassi et al., 2021). Recent works demonstrated the possibility of combining two urban side-streams (OFMSW and sewage sludge from Treviso municipality – Northern Italy) to produce PHAs (with a yield from 7.6% to 10 % on volatile solids) alongside biogas and digestate (Moretto et al., 2020; Valentino et al., 2021), in a biorefinery-based pipeline, where the original raw material is completely valorised in accordance with the cascading principles. A recent review listed several examples of exploitation of OFMSW for PHAs production, comparing with the synthesis from other bio-waste types (Gottardo et al., 2022). In addition, the production of PHAs from bio-waste has been evaluated in terms of consumer perception, to assess the willingness-to-pay for, buy and switch to bio-based products (Russo et al., 2019).

Organic acids are relevant compounds to be considered as well, since their role on the market and applications in several sectors, especially when polyfunctional (Di Lorenzo et al., 2022). Indeed, molecules such as succinic acid and lactic acid have been proposed to be produced from urban bio-waste, often in combination with other products, in order to improve OFMSW management feasibility both from the economic and environmental point of view (Babaei et al., 2019; Khoshnevisan et al., 2019, 2020; Zaccariello et al., 2020). Succinic acid was obtained from the hydrolysed organic fraction of household kitchen with a yield of 46 % g/g sugars (Babaei et al., 2019). Integrated production strategies can enhance their appeal in urban scenarios. As examples, lactic acid, biogas and hydrochar (Zaccariello et al., 2020), or lactic acid, succinic acid and single cell protein (SCP) (Khoshnevisan et al., 2020) can be mentioned as demonstrating promising approaches.

Enzymatic approaches for OFMSW treatment

Enzymes are biocatalysts with a prominent role in the biorefineries scenario as substitutes or in combination with chemo-physical pre-treatments of biomass before fermentations, as mentioned above, or for transforming platforms into final products, as part of the cell factories or of a tailored biocatalysis. Enzymes are macromolecules of biotechnological interest for several industrial areas such as food, detergent, textile and pharmaceutical. In respect to OFMSW, enzymatic treatments aim to hydrolyse recalcitrant molecules such as crystalline cellulose, keratin and starch to monosaccharides or amino acids, in order to promote microbial actions and/or increase the efficiency of fermentation performances. A recent study showed that the enzymatic hydrolysis of the OFMSW could increase its methane potential from 189.2 mL/gVS to around 672 mL/gVS after AD (Mlaik et al., 2019). This study is also interesting because the enzymatic cocktail, made of several carbohydrases such as α-amylases and β-glucosidases, was produced by *Aspergillus niger* by using OFMSW as growth media.

In addition to hydrolytic pre-treatment of biomass, cell-free approaches have been developed in order to carry out partial or entire metabolic pathways to produce compounds of interest without the limits imposed by microorganisms management. Studies have shown that spent coffee grounds can be transformed into lactic acid by the use of cell-free multienzyme cascade with a yield up to 70 %, with the advantage of overcoming microbial-related problems, such as product toxicity, internal regulation and restricted range of thermostability (Kopp et al., 2019). Enzymes can be also used in synergy with the microbial process. An example is the use of free laccase enzymes, specific for the oxidation of lignin, that could be employed in synergy with *Rhodococcus opacus* to increase the yield of lipid production (Zhu et al., 2015).

In addition, with respect to physico-chemical reactions, enzymes usually require milder conditions of temperature and pH and are carried out in aqueous solutions, allowing a reduction of energy and waste disposal costs. In summary, an enzymatic approach can be a valid alternative to the traditional chemo-physical pre-treatments, for example in terms of safety for both the operators and the environment (Chakraborty et al., 2023).

Despite the mentioned advantages, an enzyme-based biotransformation requires the knowledge of the pathways leading to the product release, together with the identification and production of the enzymes involved, that can be time-consuming and expensive; in addition, not all the enzymes have the characteristics of solubility and stability required by the process, which can limit their use in industrial setups.

How to drive bio-waste valorisation

Considering all the viable processes previously described that can be performed on biomass and the actual urban context, we identified at least three fundamental elements that must be considered in sustainable urban development programs. The first concerns the characteristics of the available bio-waste in terms of quantity, accessibility, and homogeneity. The second element concerns the technologies to be adopted for the transformation processes, taking into consideration the strategies described above or their combination, to overcome the limitations related to the single procedures. The third refers to territorial economic policies which must identify effective levers to promote circular processes for local waste.

We report some examples that take into account all these three aspects. In the last few years some virtuous examples started to emerge such as the collection and employment of hair. This organic bio-waste, with a homogeneous composition and concentrated in specific urban places (hair salons and groomers), does not require conservation methodologies. In most cities, this kind of waste is commonly collected in landfills, where its slow degradation leads to prolonged occupation of large spaces. For this reason, more and more organizations are collecting it separately in order to exploit its full potential. First, hair can be added in adequate proportion to the organic waste to produce good quality compost due to its nitrogen-rich composition (Waliczek et al., 2021). Moreover, recent papers showed alternative efficient valorisation strategies such as pyrolysis for the production of biofuel (Krishnakumar et al., 2023) and the extraction of keratin and melanin for medical uses (Mukherjee et al., 2023). In addition, some bacteria strains such as *Bacillus subtilis* AMR have been shown to produce keratinases by using hair as a substrate for growth (Cai & Zheng, 2009; Mazotto et al., 2010). It is therefore a question of activating differential collections and selecting the most suitable technologies also based on a socio-economic analysis of the territory and the availability of facilities.

Another emblematic case is represented by the spent coffee ground (SCG), a bio-waste obtained by the brewing of coffee and largely produced worldwide, with an estimation of 60 million tons (Forcina et al., 2023). Today, this bio-waste is commonly used to produce compost (Zhang & Sun, 2017). However, in the last few years many start-ups and companies have been evolving around this bio-waste in order to produce or extract high-value molecules. Several studies have shown that solid-state fermentation of SCG can be used to improve the extraction of antioxidant compounds such as caffeic acid, beneficial for human health, as well as other phenolic compounds with an improved yield of 2.3-fold with respect to the hydroalcoholic extraction alone, but with a longer process (Arancibia-Díaz et al., 2023; Rochín-Medina et al., 2018). Compounds such as PHAs, mentioned above, can be produced from SCG with the use of bacteria such as *Pseudomonas resinovorans* (Kang et al., 2023), as well as flavours, oils and carotenoids. An interesting use of this bio-waste includes the production of alcoholic beverages potentially suitable for human consumption, with distinct organoleptic properties due to flavours and aroma naturally contained in this biomass (Machado et al., 2018). In case SCG is valorised by the same companies producing coffee as a food product, logistics is no longer a limitation.

The advantage of operating on urban biomass is the volumes, which are large thanks to the high concentration of citizens, and the waste sorting and logistics since they are produced in delimited areas. An example is the biomass generated during urban maintenance. This biomass is growing also thanks to the urban forestation promoted by Green Deal strategies. In most cities, this bio-waste can be used to obtain compost. However, as mentioned before, green biomasses could be better valorised in a large array of different final compounds, as they can undergo microbial processes to produce biofuels, biogas and biodiesel and also a large number of bioactive compounds by using specific chemical or microbial agents (Ahmad et al., 2022). Table 1 summarizes some examples disclosed in this document (plus additional cases), with a specific focus on the yield of the final product, starting from several biomasses of urban origin.

Best practices for urban bio-waste valorisation

As highlighted in the introduction, urban biomass valorisation is hampered by the current lack of value creation models, integrated in urban environments and capable of offsetting waste management costs (European Compost Network ECN, 2022). This last section aims to present a set of good practices tested in cities, that deliver products with a market value, as well as social and environmental ones. Three cases have been selected, one for each urban bio-waste category identified in the previous paragraphs: food waste; urban green spaces and garden waste; “other”, which includes particular types of bio-waste that can be collected and treated through dedicated valorisation chains (*e.g.* human hair, pet fur, textile waste, spent coffee grounds).

Table 1
Examples of urban bio-waste valorised in biorefinery processes to obtain products of industrial relevance.

Biomass	Process	Final product	Yield/Value	References
Hair	Chemical	Bio-oil	20 % (5 MJ/kg)	(Krishnakumar et al., 2023)
	Chemo-enzymatic	Melanosomes	1.3 % (w/w) melanosomes	(Zhang et al., 2022)
Spent coffee ground (SCG)	Biotech	PHAs	1.6 g/L (from oil-extracted SCG)	(Kang et al., 2023)
	Biotech	Carotenoids	1.1 mg/g biomass	(Petrik et al., 2014)
Textile	Biotech with chemo-enzymatic pre-treatment	Ethanol	70 % (g_{EtOH}/$g_{cellulose}$)	(Gholamzad et al., 2014)
OFMSW	Biotech	Compost	40–45 % (w/w)	(European Commission, 2001; Pavlas et al., 2020)
OFMSW	Biotech	Biogas	100 Nm^3/$t_{biowaste}$	(European Commission, 2001; ISPRA, 2022; Pavlas et al., 2020)
OFMSW + sewage sludge	Biotech	PHAs	up to 10 % (w/w)	(Moretto et al., 2020; Valentino et al., 2021)
Hydrolysed organic fraction of household kitchen	Biotech	Succinic acid	46 % g/g sugars	(Babaei et al., 2019)

Selected cases meet the following criteria: they have been implemented in urban contexts; they enable the valorisation of urban bio-waste and contribute to the generation of new products, closing related cycles; they represent innovative approaches and experiences, as they have been tested through pilot projects; they have delivered social and environmental benefits; they are potentially replicable in other parts of EU.

Good practices of urban biomass valorisation have been identified through desk analysis and screening of several sources, including the EU “Circular Cities and Regions Initiative” (European Commission, 2024a), the online database of EU-funded projects (European Commission, 2024b), and the “Good practice database” of the European Circular Economy Stakeholder Platform (ECESP) (European Union, 2024).

The cases are described through a similar structure, including key elements such as waste type, valorisation process, key products, value proposition, stakeholders involved and their roles, main results, and benefits obtained.

Considering food waste, cities are a relevant source of this waste category in the post-consumption phase (Fattibene et al., 2020) and food represents a relevant share of urban organic waste. The case study presented here refers to the private company “The Waste Transformers” (The Waste Transformers, 2024), established in Amsterdam (The Netherlands) (Fig. 3).

An on-site closed anaerobic digester for food waste treatment (up to 3600 kg each day) was initially tested at Westergasfabriek in Amsterdam (The Netherlands), a former gas plant regenerated to a park and commercial services, which produces a relevant amount of food waste. Such material is converted into electricity and heat or biogas, while recovering water and nutrients for fertilization. The latter is used directly to improve the park soil quality, whereas the residents can purchase local electricity generated by the digester. Therefore, the collaboration between the private company that developed the on-site digester, and the commercial partner or community that provides the food waste is fundamental for the operation of this solution. The initiative has later expanded to other countries, including Sierra Leone and Colombia. The company has also launched an “entrepreneurs development program”, where selected candidates in emerging economies are trained and provided with funding, legal, and technical support to run a standalone small-scale waste transformer as an individual business. The Waste Transformer is an example of on-site solution that valorises food waste into different outputs, which can be implemented also in urban contexts. The value proposition comprises waste upcycling, green energy, and green fertilizer production, as well as the enhancement and diffusion of entrepreneurial capacities and opportunities in the circular economy sector.

Regarding the category of “urban green waste”, the city of Apeldoorn (NL) has tested several solutions to upcycle bio-waste generated in green public spaces, in particular grass, leaves, pruning, and weed, through a set of demonstrators within the “CityLoops” EU-funded project (CityLoops, 2024). The case selected for this review regards the utilization of leaves collected within public spaces to produce “bokashi”, a form of compost obtained through a fermentation process, rather than a general decomposition of organic matter (Fig. 4).

The project was conducted through a collaboration among several departments of the Apeldoorn municipality and Wageningen University together with the direct involvement of inhabitants, in activities such as collecting leaves, cleaning up the roads, and driving tractors. When the bokashi was ready, city employees spread the compost in the neighbourhoods. The municipality also implemented communication initiatives to inform the citizens.

Considering the results, the demo showed that bokashi from leaves on average has more organic material (45 %) than locally produced compost (32 %) and certified produced compost (26 %) (Hellemans et al., 2023). Further aspects like the presence of macro-nutrients,

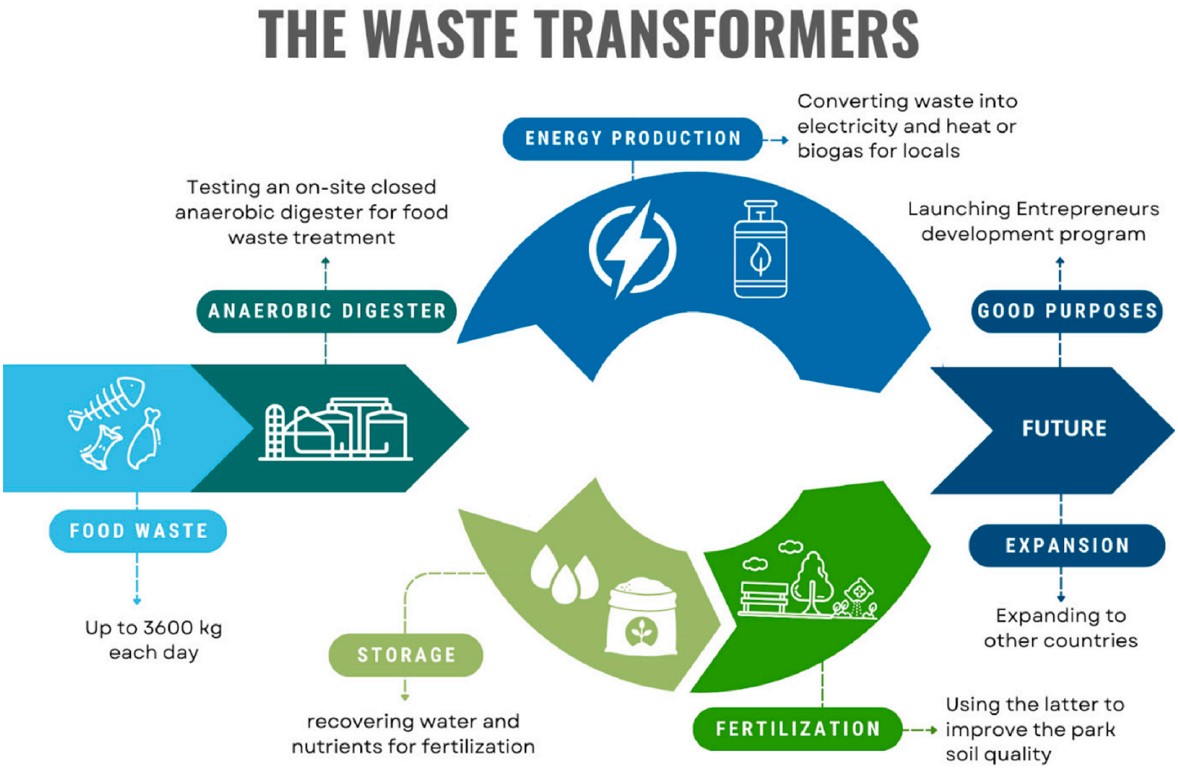

Fig. 3. Graphical representation of the processes of the Waste Transformers (NL).

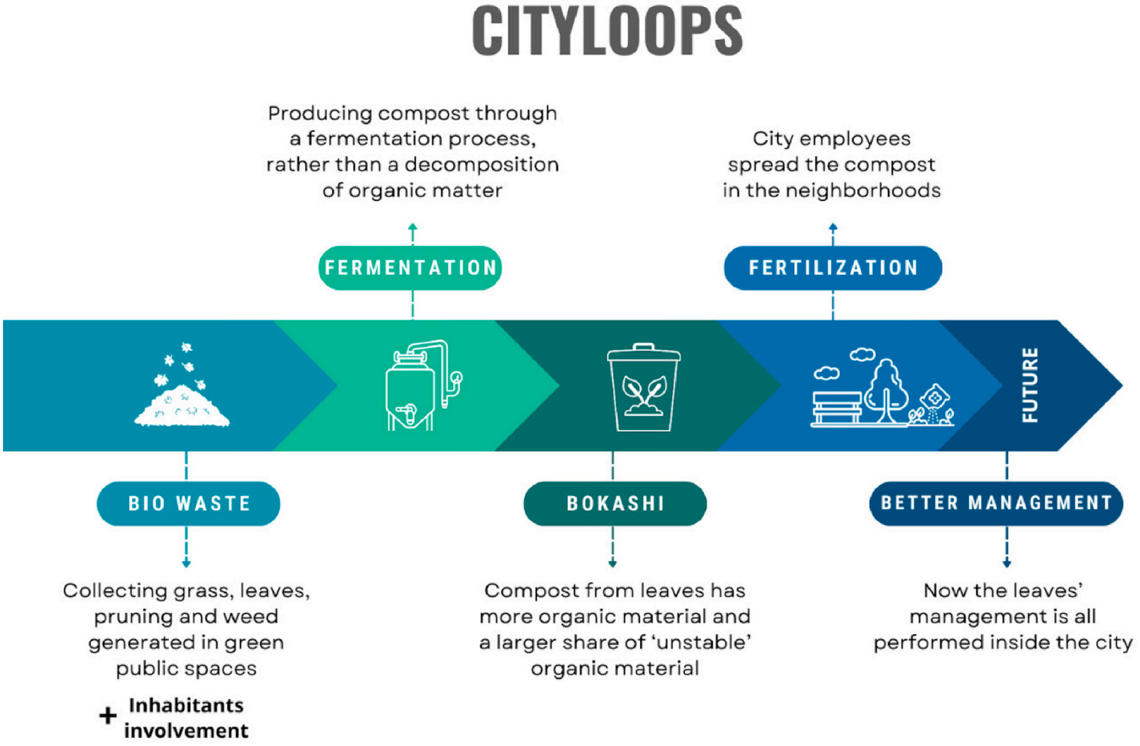

Fig. 4. Graphical representation of the processes of Cityloops in Apeldoorn (NL).

micro-pollutions, pesticides, heavy metals, and arsenic showed no significant differences. Before the demonstration, leaves collected from public spaces were exported from the city and composted regionally. The compost was then bought and imported for urban soil. With the demonstrated solution, the leaves' management is performed inside the city. The value proposition of this model is to enhance public spaces, being an approach compatible with the city's green area management strategy. Nonetheless the city of Apeldoorn is comparing bokashi with other solutions such as leaves' mulching to determine the performances. The decision to opt for bokashi will therefore depend on the long-term results in terms of soil quality.

Regarding the category “other”, among the specific value chains identified for possible valorisation, an example of spent coffee ground (SCG) upcycling has been selected as a case study. As mentioned in previous paragraphs, SCG has a relevant potential for recycling, thanks to the high volumes produced worldwide, in particular in cities where a large number of cafeterias, restaurants, and customers are located. Furthermore, this waste stream can be easily collected in a separate way, which improves the treatment and upcycling process. The selected case study refers to the social cooperative PermaFungi (PermaFungi, 2024), established in Brussels (Belgium) in 2014, that collects and recycles coffee grounds waste to produce oyster mushrooms, chicory, organic material, and compost. The residues of oyster mushroom production (“champost”) are further upcycled to grow a biodegradable material named “myco-material”, which can be used for creating design objects, thermal insulation, or packaging to replace some plastic materials (Fig. 5). According to the cooperative, the production process of myco-material is less intensive in terms of CO_2 production and energy consumption than the production of polystyrene foam (generating ten times less CO_2 and using about eight times less energy). From a social and economic point of view, the cooperative has implemented a training program to share their cultivation techniques and expand the network of factories in different cities.

PermaFungi is an example of a social enterprise that has promoted an innovative business model, where the value proposition is focused on the production of healthy food and materials through a circular and on-site (city-scale) approach while targeting environmental and social promotion purposes. The production process is potentially replicable in other city contexts and enables the valorisation of a relevant waste stream at the urban level.

The three selected cases show innovative approaches for urban biomass valorisation that can be applied in city contexts and aim to produce economic, social and environmental value in terms of new products, resource savings, job opportunities, training, community involvement, and link to urban regeneration processes. The discussion of the three cases has not taken into account the economic viability of the models, due to a lack of comparable and comparative data on capital and operational costs as well as revenues. This aspect should be explored in a dedicated analysis.

The potential market for bio-based products is considered to be growing, driven by environmental and climate policies, corporate social responsibility and rising consumer demand for sustainable products. At the same time, several barriers limit a further expansion of markets for products originated by circular processes. Looking at the products obtained in the three analysed cases (*i.e.* organic mushrooms, organic fertilizer and biogas), some market insights can be drawn from available studies. Considering organic food, per capita consumer spending has doubled in the last decade in the EU and has grown globally (Willer et al., 2022). With reference to composting and organic fertilizers, there are a variety of potential applications of compost depending on its quality, nutrient content and other chemical parameters, therefore the market can be different according to these characteristics (Plana, 2015). In the case analysed in the paper, the production of fertilizer served mainly a public purpose to increase public soil quality instead of aiming to reach the market. Finally, considering green energy, biogas is among the fastest growing forms of bioenergy, and according to IEA it will play a relevant role in supporting energy transition in local communities and municipalities together with renewable electricity (International Energy Agency, 2020).

Overall, the large quantities of the three analysed bio-waste types in cities is a favourable condition for further upscaling, adoption and transferability of these practices in other urban contexts. However, the specificities of the local context, market conditions and demand, as well as production and upscaling costs should be taken into account to assess their actual potential in more detail.

In particular, the economic advantages that emerge from these case studies are the following:

- for companies with residual food-waste, reduction in disposal costs, savings on management costs and generating new revenue streams in

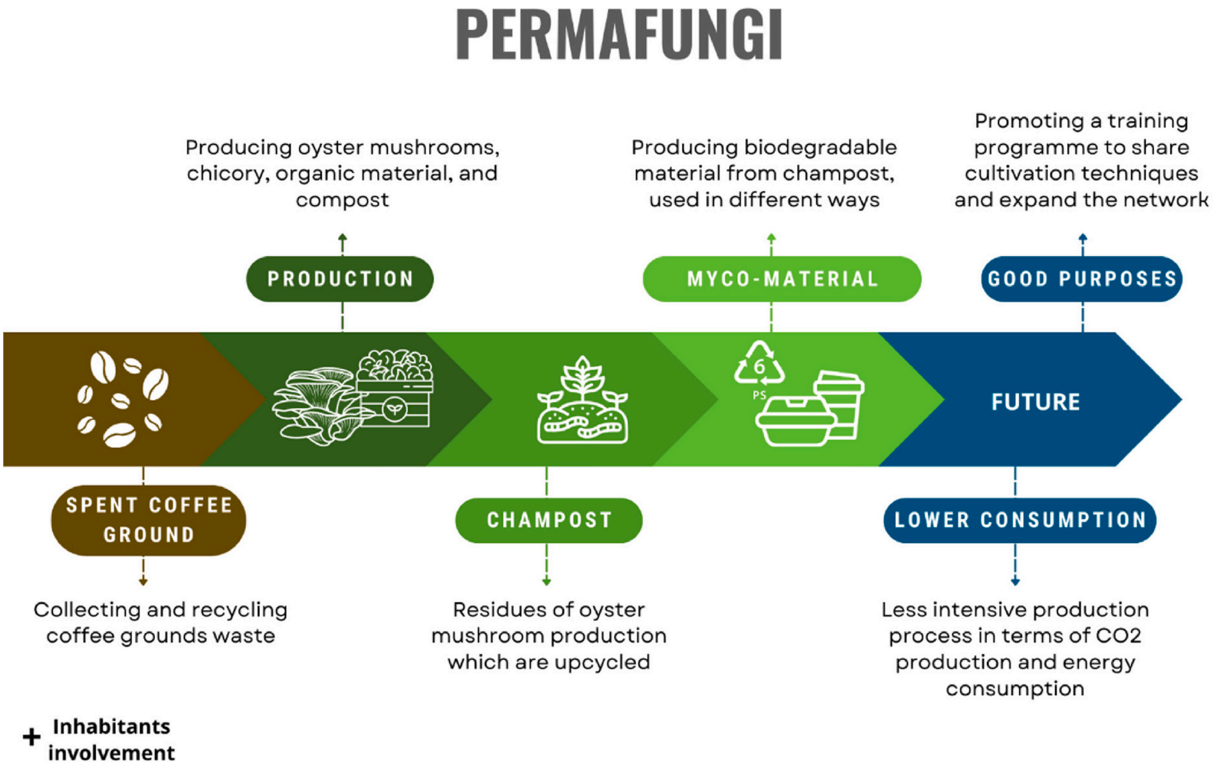

Fig. 5. Graphical representation of the processes of PermaFungi (Belgium).

the long term: once the internal reuse system or the synergy with a dedicated company is established with starting investments, in the long term the costs associated with the price of waste disposal is substituted with the production of materials that can be employed again in the production chain or with the income of their sale (*i.e.* biogas or fertilizer trading, carbon credit earning system) (Trouwloon et al., 2023).

- creation of new business opportunities: the bio-waste stream treatment favors creation of new strategic partnerships between companies, increasing the value chain and the commercial opportunities ("Industrial symbiosis"). Moreover, biorefineries allow for the production of a wide variety of goods, diversifying revenue streams and reducing reliance on individual markets (Calvo-Flores & Martin-Martinez, 2022; European Commission, 2016) and job positions.

However, some deeply rooted obstacles still emerge at various levels. We believe it is important to summarize them in order to analyze them further and, consequently, find ways to overcome them:

- Regulatory complexity in this transition moment: long bureaucratic processing times (often related to still not clear norms and inadequate cooperation between different actors *i.e.* public entities, companies and citizens) delay bioconversion plant installation.
- The lack of awareness among consumers and businesses about the benefits of the circular economy limits the adoption of bioconversion technologies. Moreover, the shortage of internal expertise within companies represents a significant barrier.
- High costs and initial installation investments, often a barrier for small and medium-sized enterprises without incentives. Moreover, the return on investment can be slow due to the complexity of the process and the variability of prices on final products.
- There is still room for improvement from the technological point of view of the existing processes, as we described in the dedicated session. Moreover, the lack of adequate infrastructure for the collection and the transportation of bio-waste can hinder bioconversion efficacy.
- Cultural resistance (such as inertia in behaviors, both of individual citizens and policymakers), distrust towards emerging technologies, often not given much consideration unless local communities are involved, lack of active involvement of citizens and entrepreneurs, conflicts of interest in employment of public spaces for bio-waste treatments in urban areas.

Conclusion

Urban bio-waste is gaining increasing attention, both scientifically and institutionally, due to its steadily growing quantities. The turning point for managing its treatment in alignment with the objectives of the European Green Deal is to establish conditions that allow it to be perceived as an active resource rather than a waste disposal problem. Traditional disposal methods, such as incineration and landfilling, as well as emerging ones like composting and anaerobic digestion, when considered individually, present evident disadvantages and limitations. Firstly, the former two are highly polluting, promote inefficient land use, and indiscriminately destroy all components without generating value or profit. Secondly, the two emerging methodologies, although already being implemented, are not particularly efficient on their own, and their resulting products lack diversification or added value, making it difficult to justify the initial investments needed to build the required infrastructure. A detailed analysis of bio-waste composition, which can be categorized into food-origin, garden-origin, and other niche but less heterogeneous waste (such as hair, spent ground coffee, or butchery residues), clearly highlights both its variability and the richness of substances that can be harnessed to generate value. We identify three key drivers for bio-waste valorization:

1. Boosting separate collections, with suggestions such as developing technologies for sorting or implementing door-to-door collection to actively involve citizens.
2. Ensuring sufficient quantities to establish a solid and reproducible supply chain.
3. Strengthening synergies by creating urban biorefineries capable of fostering collaboration among multiple entities and businesses to amortize costs and generate profit by integrating various technological processes to cover the entire bio-waste treatment chain.

In this regard, this review provides detailed examples of both innovative and optimized existing processes, ranging from biological treatments such as enzymatic treatments and various fermentation processes that generate high-value products (not just low-value ones) like platform chemicals or bioplastic polymers, to thermo-chemical processes such as pyrolysis, hydrothermal treatment, active component extraction, or conservative upcycling, which can be applied, for example, in 3D printing. Each of these processes has individual advantages and disadvantages, but the study of their synergistic action on various substrates and different process steps represents what we consider the true turning point. For this reason, we have included a case study for each category of bio-waste that is currently operational in Europe. While specific economic values are not disclosed and are beyond the scope of this review, the business model, the methodology followed, and the outputs are replicable beyond individual contexts. We have not overlooked the current barriers to implementing this urban circularity approach: regulatory complexity and ambiguity, lack of awareness and cultural resistance, high costs and initial installation investments, and limitations in individual technological processes. However, analyzing these barriers helps us understand the strategic steps needed to overcome them. We conclude by emphasizing that focusing on bio-waste is of fundamental importance and brings economic benefits (reduction in disposal costs, savings on management costs, and generating new revenue streams in the long term, creation of new business opportunities), social advantages (overcoming inertia-related barriers to behavioral change through activities that increase awareness and foster a sense of local community), and, consequently, benefits to institutions, citizens and stakeholders.

CRediT authorship contribution statement

Jessica Frigerio: Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Stefano Bertacchi:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Sara Mecca:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Stefania Digiovanni:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Tania Molteni:** Writing – original draft, Investigation. **Valeria Mapelli:** Writing – review & editing. **Luca Beverina:** Writing – review & editing, Writing – original draft, Conceptualization. **Marina Lotti:** Writing – review & editing, Writing – original draft. **Edoardo Croci:** Writing – review & editing, Writing – original draft, Conceptualization. **Paola Branduardi:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Massimo Labra:** Writing – review & editing, Writing – original draft, Validation, Funding acquisition, 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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