Organic recycling of post-consumer /industrial bio-based plastics through industrial aerobic composting and anaerobic digestion - Techno-economic sustainability criteria and indicators

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Abstract

The sustainability assessment of alternative EoL routes for the post-consumer /industrial bio-based plastics should ensure that these waste streams are routed to the optimal options that would allow, as a first priority, for their recirculation as valuable secondary bio-based resources, in support of the circular bioeconomy. Organic recycling, is considered as the second preferred alternative End-of-Life (EoL) option, for post-consumer /industrial biodegradable bio-based plastics that are characterised as mechanically/chemically non-recyclable. Techno-economic sustainability criteria and indicators are proposed based on an extended literature review to assure the technical feasibility and economic viability of organic recycling for these products. The proposed TESA methodology for organic recycling is organised into 3 integrated TESA Criteria: a) "Technical feasibility"; b) "Economic viability"; c) "Common techno-economic – environmental" criteria, including TESA criteria that are used also as environmental sustainability assessment criteria through LCA. The recirculation potential TESA criterion has a much lower importance for organic recycling as compared to material recovery. A set of indicators, evaluated by relevant metrics, are proposed for the assessment of the corresponding techno-economic criteria. The overall assessment of the organic recycling options for bio-based biodegradable plastics, requires a parallel assessment based also on environmental and social sustainability criteria. These criteria are beyond the scope of the present work.

Keywords: Techno-economic sustainability, bio-based plastics, biodegradable plastics, plastic waste streams, organic recycling, aerobic composting, anaerobic digestion, circular bioeconomy

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Nomenclature	
BCBs	Bioplastic carrier bags
BNCs	Bio-nanocomposites
CNCs	Cellulose nanocrystals
DS	Digested sludge
ES	Excess activated sludge
LS	Laboratory sludge
MB	Mater-Bi
MCE	Microcrystalline cellulose
QAC0.4	Methyl, tallow, bis-2-hydroxyethyl, quaternary ammonium (0.4% surfactant)
RAC	Residual ash content
TBW	Thermally treated biowaste
T_{cc}	Cold crystallization temperature
T_g	Glass transition temperature
T_m	Melting temperature
TOC	Total organic carbon
TS	Total dry solid
VS	Volatile solids
WC	Water content
WHC	Water holding capacity
WWS	Wastewater sludge
TAC	total inorganic carbon, estimation of the buffer capacity of the sample
FOS	volatile organic acids
FOS/TAC ratio	Measure of the stability of the digester
M_w	Weight average molecular weight
M_n	Number average molecular weight
M_v	Viscosity-average molecular weight

1 Introduction

1.1 Alternative EoL options for post-consumer/ industrial bio-based products

A new road map with ambitious targets for materials recycling and for banning landfilling has been introduced by the European Commission through the Circular Economy Package (CEP) [1,2], approved by the European Parliament and the Council, that replaced the Waste Framework Directive (WFD) [3]. The new road map aims at boosting the re-circulation of secondary materials in the production of new products and eliminating landfilling as a waste management option. The alternative End-of-Life (EoL) routes are hierarchised in CEP [1,2] with priority placed on waste prevention followed by the preparation of post-consumer products for re-use. The priority for aternative valorization options of various waste streams are set as follows: materials recovery, organic recycling, energy recovery, and disposal.

CEP [1,2], along with the recently approved Circular Economy Action Plan [4], support in several ways the circular economy with the resources being re-circulated and re-used through industrial symbiosis. In parallel, the EU Strategy for Plastics in the Circular Economy [5] promotes the design and production of plastics with high recyclability. More specifically, all plastics packaging should be mechanically recyclable by 2030. Another important objective set by CEP is the separate collection of various waste streams. The use of biomass as feedstock for the production of bio-based plastics in combination with the circular economy principles supports the circular bio-economy model. Furthermore, Directive (EU) 2019/904 aims at banning /controlling the ten most threatening single-use plastic products for marine littering, as well as oxo-degradable plastics [6]. Major challenges to achieve all these objectives remain the efficient implementation and sustainability of the actions undertaken.

An average quantity of 489 kg of municipal waste per capita, with a range of 272 - 766 kg per capita, were generated in 2018 in the EU-28 [7]. The total municipal waste generated in 2018 was estimated at 251 Mt. The shares of the alternative treatment categories of this waste quantity were distributed as follows: recycling through material recovery: 30% (75 Mt); landfilling: 23% (57 Mt); incineration: 28% (70 Mt); composting: 17% (43 Mt); other: 2% (6 Mt) [7]. The plastic production data for 2018 was 61.8 Mt in EU-28 and 259 Mt the global plastics production. The collected post-conumer plastics in the EU for 2018 was 29 Mt and the corresponding data for their treatment were as follows [8]: recycling: 32.5% (9.4 Mt, 18% outside EU); landfilling: 24.9% (7.2 Mt); incineration: 42.6% (12.4 Mt). The reported shares of the treatment categories of the collected post-consumer plastic packaging waste for 2018 (17.8 Mt) were: recycling: 42% (7.5 Mt); landfilling: 18.5% (3.3 Mt); incineration: 39.5% (7.0 Mt).

These figures should be compared against the new targets set by CEP for the alternative EoL options of the municipal waste, that should be met by 2035: recycling 65% with 70% and 55 % for packaging and plastic packaging waste, respectively, by 2030; landfilling: 10% maximum, with ban on landfilling of separately collected waste. Bio-waste has to be separately collected by 2023. This comparison reveals that the recycling rate is lacking behind by more than 50% of the targeted value, while landfilling needs to be reduced by more than 50%. Furthermore, the single use plastics are already banned, considered responsible for contributing significantly to marine littering,

The available alternative EoL routes for post-consumer /post-industrial bio-based plastics are presented in the inventory of [9]. This inventory includes a detailed presentation of both, the industrial aerobic composting and anaerobic digestion (AD) treatments.

According to survey data provided by the European Compost Network (ECN) [10], an estimated annual quantity of 30 Mt of bio-waste, separately collected, is composted or digested in approximately 3500 industrial aerobic composting or AD facilities across

Europe. A share of more that 50% of the separately collected bio-waste belongs to the category of green waste, processed into compost in more than 2000 aerobic composting plants. In total, 90% of the green waste and food waste streams in EU are routed to composting, which is a preferable way of treatment of biowaste over AD [10]. A compost quantity of 11.7 Mt was produced during the period 2016-2017 in EU, despite the limited contribution by 14 member states. On the average, this compost contained approximately: 129 kt of nitrogen (N), 42 kt of phosphate (P) and 3.5 Mt of total organic carbon (TOC). Taking into consideration the obligation for compliance by all member states with the new requirement for separate collection of bio-waste by 2023, significantly larger quantities of certified high quality and safe compost are expected to be produced across Europe, meeting also the fertilising products Regulation specifications [11].

1.2 Techno-economic sustainability of bio-based plastics

The terminology of EN 16575 [12] is adopted for the bio-based plastics, classified into [9,13]: a) bio-based non-biodegradable plastics with the same chemical structure as their fossil-based counterparts (drop-ins); b) bio-based biodegradable plastics, certified according to relevant standard specifications as biodegradable in specific environment(s).

According to European Bioplastics [14], the bio-based plastics global production capacity in 2019 was 2.11 Mt (0.94 Mt non-biodegradable, 1.17 Mt biodegradable), estimated to increase to 2.43 Mt by 2024 (1.10 Mt non-biodegradable, 1.33 Mt biodegradable). Especially for non-biodegradable plastics, bio-PP is expected to grow six-fold while biodegradable polyhydroxyalkanoates (PHAs) are expected to grow three-fold by 2024 [14]. The quantity of bio-based plastics, even though still low as compared to the annual global plastics production of 360 Mt, is continuously increasing.

The sustainability assessment of the life cycle of bio-based products, requires the sysnthesis of the environmental, social and techno-economic sustainability assessment [15,16,4]. The techno-economic analysis (TEA) [17,18] allows for both, qualitative and quantitative analysis of the financial viability and technical feasibility of the various stages of the life cycle of bio-based plastics but lacks the dimension of sustainability [9]. The sustainability dimension is incorporated into the TEA through the Techno-Economic Sustainability Analysis (TESA)[9,19] as defined in [19].

A methodology was developed in the framework of the STAR-ProBio project, [20,15] for the environmental, social and techno-economic sustainability assessment of bio-based products over their whole life cycle (bio-based resources, processing and alternative EoL routes). The sustainability assessment of alternative EoL routes for the post-consumer /industrial bio-based plastics should ensure that these waste streams are routed to the optimal options that allow, as a first priority, for their recirculation as valuable secondary bio-based resources, in support of the circular bioeconomy [21,22].

1.3 Scope of the present work

Even though the contemporary quantities of (nonrecyclable) biodegradable bio-based plastics routed to organic recycling, represent a very low percentage of the total organic recyclable waste (bio-waste, green-waste), their organic recyclability is a major issue since:

- The bio-based plastics sector develops dynamically, and the need to investigate all the alternative preferred EoL options is imminent.
- Some recent examples: already EU legislation has banned single use non-biodegradable plastics. These are replaced by recyclable and biodegradable/compostable articles which, in cases recycling is not feasible or viable, are routed to organic recycling. Plastic bags used to collect bio-waste for composting should also be compostable.

- If (and only if) the only possible EoL option of post-consumer biodegradable plastic is organic recycling (e.g., nonrecyclable contaminated by organic waste), the organic recycling industry should assure that the presence of plastic in the organic waste stream will contribute to, or at least will not interfere negatively with, the current operating procedure.
- The absence of extensive field experience on this issue, makes it necessary to analyse the sustainability parameters specific to the post-consumer bio-based plastic stream during organic recycling.
- In a similar manner, society wants to analyze and quantify all sustainability aspects of a plastic product throughout its life. This includes the EoL options and among them the organic recycling alternative

The present work focuses on organic recycling, as the second alternative EoL option, for post-consumer /industrial biodegradable bio-based plastics characterised as mechanically/chemically non-recyclable (the term "*non-recyclable*" from now on implies "*mechanically/chemically non-recyclable*"). Techno-economic sustainability criteria and indicators are proposed to assure the technical feasibility and economic viability of organic recycling for these products. The overall assessment of the organic recycling options for bio-based biodegradable plastics, requires a parallel assessment based on environmental and social sustainability criteria (e.g. [23]). The application of the proposed TESA criteria for organic recycling in selected case studies is the subject of research work in progress.

2 Methodological approach

2.1 Prioritised routes for post-consumer/industrial bio-based biodegradable plastics

The hierarchical principles of CEP [1,2] and WFD [3] set the material recovery through mechanical and chemical recycling (recyclates and monomers/oligomers) and their recirculation through industrial symbiosis as the preferred EoL option for all plastics [9].

The second preferred EoL option according to CEP [1,2] and WFD [3] for the biodegradable post-consumer/industrial bio-based plastic streams that do not meet the TESA (and environmental, social) criteria for material recovery, or they are rejected from the corresponding recycling facilities, is organic recycling under controlled conditions: aerobic industrial composting and anaerobic digestion (AD).

A usual confusion concerning biodegradable plastics, widely spread among the public and stakeholders, including industries, may be expressed as follows: *"Are post-consumer /industrial bio-based biodegradable plastics designed to be routed (or should be routed) to organic recycling alternative options, including home composting, as a first preferred (or the only) EoL option"?* This misconcept is due to misunderstanding of basic organic recycling processes, the relevant legislative framework, and the regulations and EU policies concerning the circular bio-economy. It is considered important to clarify this issue first.

Organic waste (green waste and municipal or industrial organic waste) may be decomposed through organic recycling under aerobic conditions by microorganisms into useful organic fertiliser products and/or soil improvement compounds. In the case of AD, soil improvement compounds may also be produced, following an upgrade of the digestate. Biogas, a mixture of gases, mainly CH_4 (50-70%) and CO_2 (30-40%), and trace amounts of some other gases

[24], the main product of AD, can be further purified into biomethane, a valuable commercial renewable energy source.

However, biodegradable bio-based plastics certified as biodegradable routed to organic recycling follow a different path than bio-waste. These plastics are expected to biodegrade at a high degree (e.g. 90% biodegradation in less than 6 months) into CO_2, water and a small amount of biomass under industrial aerobic composting conditions. Alternatively, they biodegrade at a high degree to biogas, water and a small amount of biomass under AD conditions. In both cases, they contribute to an insignificant amout of organic mass to the final fertiliser products and/or soil improvement compounds pruduced by these facilities. Therefore, they cannot be recirculated through organic recycling in the form of organic fertilisers the way biowaste does. Organic recycling of bio-based plastics only contributes to closing the biogenic carbon loop (through aerobic industrial composting and partially through AD). In the case of AD, organic recycling partially contributes to renewable energy in the form of evolved CH_4.

The label "compostable" for a plastic product does not mean that composting is the only possible or a mandatory EoL route, particularly if the product is also labelled as "recyclable", depening on a series of TESA criteria for mechanical recyclability presented in [9].

Post-consumer/industrial bio-based plastics that according to TESA are characterised as non-recyclable and inacceptable for organic recycling (biodegradable plastics), or are rejected from the corresponding facilities for other reasons, may be routed for the production of renewable energy. However, energy recovery is not considered as one of the alternative EoL options in the waste hierarchy by CEP [1,2] because of loss of valuable materials. Energy recovery from plastics is considered as a complementary EoL treatment for materials rejected by the first two EoL options.

Another misconcept concerns home composting. The consumer should be informed that the certified compostable materials may not biodegrade under home composting conditions. Home composting is not accepted as a form of organic recycling or a legal waste treatment option by WFD, CEP, or the Packaging and Packaging Waste Directive (PPWD). A Directive amending PPWD [25] has been proposed by the European Parliament and the Council of the EU, highlighting the need for a dedicated harmonised standard for home compostable packaging. However, the draft mandate for a home composting standard has been declined by the European Committee for Standardization (CEN). According to CEN, the scope of such a standard should be limited solely to lightweight plastic carrier bags that are used by households to collect garden and kitchen waste. Draft specifications were proposed by the European Commission for the marking of biodegradable and compostable plastic carrier bags in 2018 [26]. A plan was set in 2019 for a systematic comparison of the conditions prevailing in home-composting systems across the EU and the related national frameworks.

The organic recycling window presented in Fig. 1 within the CEP hierarchy [1,2] of the prioritised alternative EoL options for post-consumer/industrial bio-based plastics, shows the connection of the centralised organic recycling routes with the first priority of materials recovery and the complementary energy recovery route. Shown are also the decentralised non-standardised home composting option and the dedicated standardised biodegradation in soil option [9].

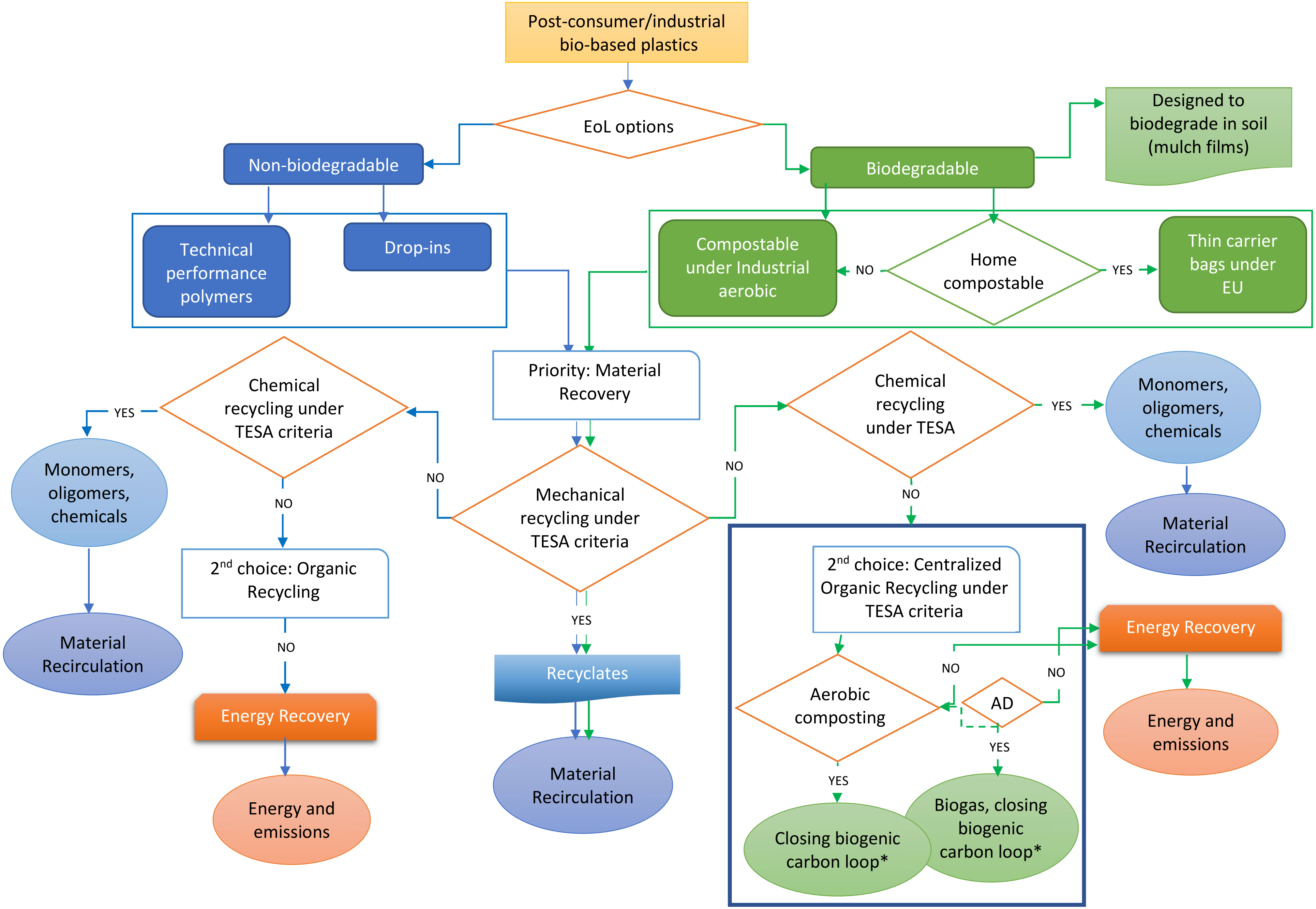
Post-consumer/industrial bio-based plastics
EoL options
Non-biodegradable
Biodegradable
Designed to biodegrade in soil (mulch films)
Technical performance polymers
Drop-ins
Compostable under Industrial aerobic
NO
Home compostable
YES
Thin carrier bags under EU
Priority: Material Recovery
Chemical recycling under TESA criteria
YES
Monomers, oligomers, chemicals
NO
Material Recirculation
2nd choice: Organic Recycling
NO
Energy Recovery
Energy and emissions
NO
Mechanical recycling under TESA criteria
YES
Recyclates
Material Recirculation
NO
Chemical recycling under TESA
YES
Monomers, oligomers, chemicals
Material Recirculation
NO
2nd choice: Centralized Organic Recycling under TESA criteria
Aerobic composting
NO
AD
NO
YES
YES
Closing biogenic carbon loop*
Biogas, closing biogenic carbon loop*
Energy Recovery
Energy and emissions

Fig. 1. The organic recycling window within the prioritisation hierarchy of the alternative EoL options for post-consumer/industrial bio-based plastics (adapted from [9]) (*) refers to the bio-based content of biodegradable products

Many research works have been dedicated to the organic recycling of bio-based biodegradable plastics [9]. However, under which conditions is organic recycling of biodegradable bio-based plastics technically feasible and economically viable? The present work proposes TESA criteria and indicators that ensure viability and feasibility of the organic recycling of post-consumer /industrial biodegradable bio-based plastics.

2.2 The organic recycling EoL routes

2.2.1 Background framework

The technical feasibility and economic viability of the organic recycling scenario for post-consumer/industrial bio-based plastics depends on several critical techno-economic parameters defined within the relevant legislative framework, in the same way as for any other EoL scenario [9]. The provisions of the legislative framework taken into consideration in this work include the CEP [1,2], Circular Economy Action Plan [4], the EU Strategy for Plastics in the Circular Economy[5], the fertilising products Regulation [11], the legislation for the organic recycling facilities [27] and other applicable EU environmental legislation. The TESA criteria for the organic recycling route of post-consumer/industrial bio-based plastics were defined in this work based on extended literature review. The inventory of the organic recycling of bio-based plastics analysed in [9] was used as the background framework.

2.2.2 TESA Criteria

The proposed TESA methodology for organic recycling is organised into 3 integrated TESA Criteria [15]: a) “Technical feasibility”; b) “Economic viability”; c) “Common techno-economic – environmental” criteria, including TESA criteria that are used also as environmental sustainability assessment criteria through LCA. The recirculation potential TESA criterion [9], has a much lower importance and it is presented as a criterion mainly to signify the key difference between the first preferred EoL option of material recovery and the second option of organic recycling, as defined by CEP [2]. A set of indicators, evaluated by relevant metrics, are proposed for the assessment of the corresponding techno-economic sustainability criteria.

2.2.3 Boundaries of the present analysis

The boundaries for the present TESA of sorted post-consumer /industrial bio-based plastics are set at the entrance of the organic recycling facility and end at the exit of the facility, with the final products (compost) to be used as organic fertilisers and/or soil improvement compounds and possibly biogas (AD facility). Even though the contribution of the post-consumer /industrial bio-based plastics to the final products of organic recycling of bio-waste is expected to be rather insignificant, it may however influence the quality of the produced compost, digestate and/or biogas, and is therefore considered in the TESA recirculation criterion.

2.2.4 Organic recycling processing

The organic recycling processing technologies for bio-waste are applicable also, possibly with proper adjustments, to handling bio-waste that contain a share of sepatately collected or efficiently sorted post-consumer /industrial bio-based plastics, provided that they are certified as compostable. Proposing realistic TESA criteria and indicators for the organic recycling of bio-based plastics requires a good understanding the basic organic processing stages.

2.2.4.1 Collection and sorting

Mixed Municipal Solid Waste (MSW) schemes, apply a fully co-mingled waste collection, associated with high cost and quality disadvantages for intensive sorting and cleaning of highly contaminated recyclable materials streams and bio-waste [28]. Recyclable multi-material collection schemes, apply a co-mingled collection of all types of source separated recyclable materials, including plastics. In this case, plastics have to be sorted out in a separate stream or in different categories of plastics streams. Recyclable mono-material schemes, apply source separation for various recyclable streams. Plastics in this case, including biodegradable and non-biodegradable bio-based plastics, are collected as a separate recyclable post-consumer plastics stream.

In both recyclable collection schemes, bio-waste may also be collected together with the non-recyclable mixed solid waste. Compost, in these cases, may be produced through mechanical biological treatment (MBT) in waste processing facilities that combine a sorting facility with some form of biological treatment. However, according to [29], compost produced in MBT plants is not suitable for agricultural aplications, ending up, in most cases, in landfills.

CEP [2] has set new targets for the separate collection of biowaste (mandatory in 2023) and other designated waste streams. In addition, tougher sustainability requirements are set by CEP [2] for evaluating if a separate collection scheme for a specific waste stream, including bio-waste, is technically, environmentally or economically practical (‘TEEP’). The separate collection of bio-waste for aerobic composting is also a requirement set by the Directive (EU) 2019/1009 [11]: *“An EU fertilising product may contain compost obtained through aerobic composting of exclusively one or more of the following input materials: (a) bio-waste within the meaning of Directive 2008/98/EC resulting from separate bio-waste collection at source*; …”. The industrial aerobic composting processes, including AD associated with aerobic composting of digestate, considered in the present work, refer to separate bio-waste collection at source.

2.2.4.2 Aerobic composting

The industrial aerobic composting technologies aim at the accelerated biological degradation and stabilization of bio-waste under controlled aerobic conditions. A wide range of organic mixed solid wastes, mainly municial organic waste and green waste, with similar rates of decomposition can be used. During the composting process naturally occurring microorganisms conssume organic material (e.g. carbon and nutrients) and oxygen. Simultaneously CO_2 and water vapours are released and heat is produced by the microbial activity. These emmissions are released in the atmosphere at approximately half the initial bio-waste materials weight [30]. In this process bio-waste is turned into a stabilised, value-added product. The valuable final condensed compost can be used as organic fertiliser or soil improvement compound provided that it complies with the relevant specifications of Directive (EU) 2019/1009 [11].

Although large variations may exist among different processing schemes and technologies, the industrial aerobic processes are divided into 3 phases as shown in the schematic diagram of Fig**. 2** [31]: a) pre-treatment, b) composting, c) post–treatment/refinement to final commercial product (compost). The different processing phases are affected by several factors that need to be monitored and adjusted [9,30,32,33,34,35,36,37]. The main processes pertaining in the three phases of the industrial aerobic composting (Fig**. 2**) are briefly presented below:

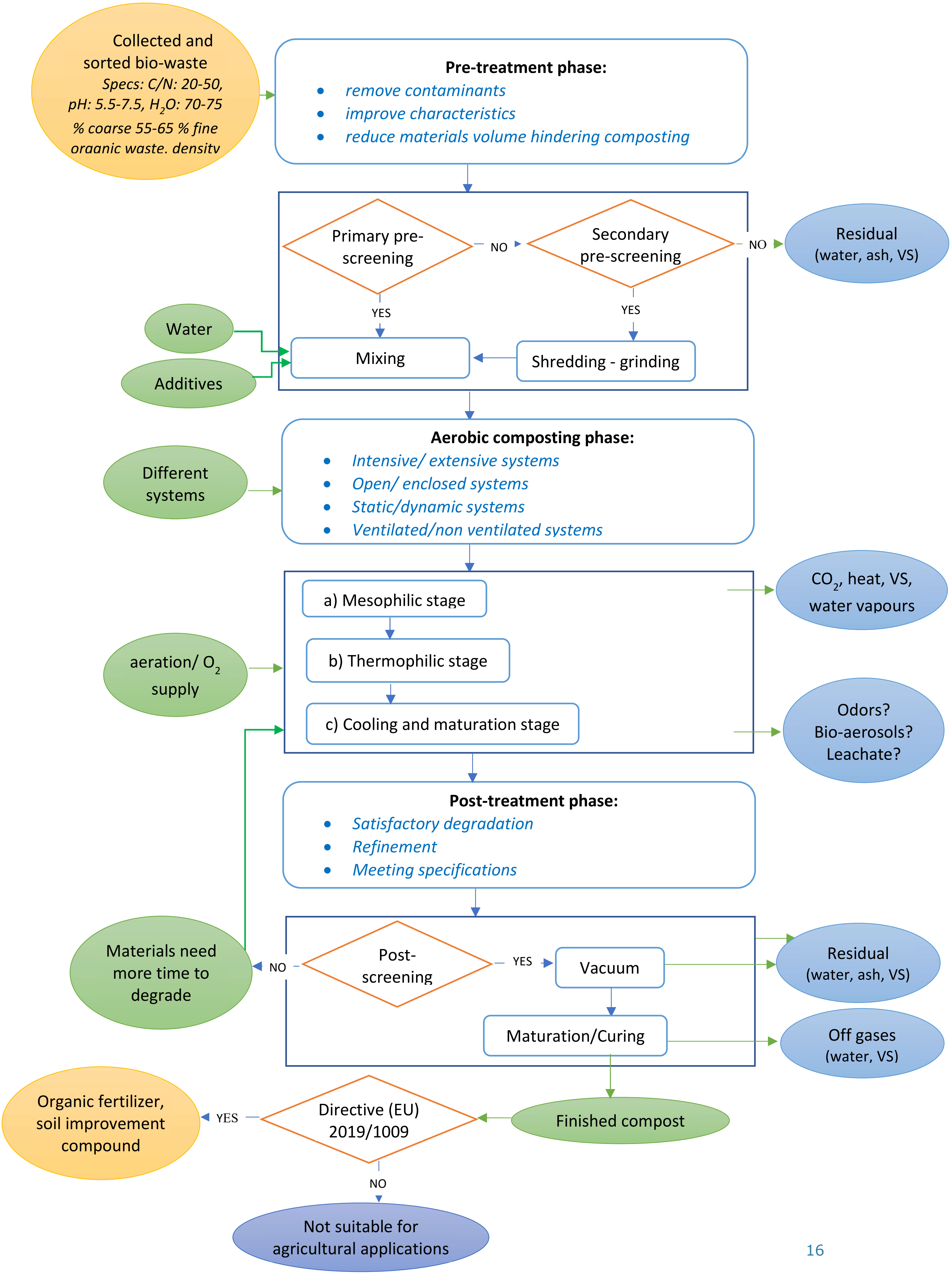
Collected and sorted bio-waste
Specs: C/N: 20-50, pH: 5.5-7.5, H_2O: 70-75 % coarse 55-65 % fine organic waste, density
Pre-treatment phase:
remove contaminants
improve characteristics
reduce materials volume hindering composting
Primary pre-screening
NO
Secondary pre-screening
NO
Residual (water, ash, VS)
YES
YES
Water
Additives
Mixing
Shredding - grinding
Aerobic composting phase:
Intensive/ extensive systems
Open/ enclosed systems
Static/dynamic systems
Ventilated/non ventilated systems
Different systems
a) Mesophilic stage
b) Thermophilic stage
c) Cooling and maturation stage
CO_2, heat, VS, water vapours
aeration/ O_2 supply
Odors? Bio-aerosols? Leachate?
Post-treatment phase:
Satisfactory degradation
Refinement
Meeting specifications
Materials need more time to degrade
NO
Post-screening
YES
Vacuum
Residual (water, ash, VS)
Maturation/Curing
Off gases (water, VS)
Organic fertilizer, soil improvement compound
YES
Directive (EU) 2019/1009
Finished compost
NO
Not suitable for agricultural applications

Fig. 2. Schematic diagram of the industrial aerobic processes

***Pre-treatment**:* The separately collected municipal bio-waste, food and green waste and possibly agricultural bio-waste and industrial organics, entering the composting facility as organic raw material (feedstock), are first characterized and treated as needed to meet the set specifications. The feedstock preparation pre-treatment steps include [31,38,39]:

- Separation: Removal of contaminants like visible non-compostable materials (e.g. plastics and glass, metals) and chemicals (e.g. household hazardous waste). According to the Directive (EU) 2019/1009 [11]: *"Furthermore, impurities in EU fertilising products derived from biowaste, in particular polymers but also metal and glass, should be either prevented or limited to the extent technically feasible by detection of such impurities in separately collected bio-waste before processing".* The incoming feedstock is effectively separated into compostable, recyclable, and disposable fractions. Metals and other recyclable materials separated and routed to recycling may become an additional income source. The separation processes implemented vary with the facility.

- Improvement of characteristics: Actions to improve the feedstock characteristics include: a) diversion of materials high in carbon content, such as yard waste and woody branches of green waste, from the incoming feedstock. These materials are shredded and screened into two streams of smaller particle size materials. The larger size particles (above 5 cm) are used as "bulky agents" to allow for better aeration of the organic mass. Aeration is the means for the needed oxygen concentration of at least 12-14% (never ≤ 5%) depending on feedstock and processing conditions. Smaller size ground particles are used as food for micro-organisms; b) shredding of high carbon materials allows for obtaining more surface area exposure and increased bulk density of raw materials (average wet bulk density 200-300 kg/m^3 that increases to 500-700 kg/m^3 during the composting process); c) conditioning to optimal moisture content: 50-60% [38] or 70-75 % for coarse and 55-65 % for fine organic waste [31] is needed; d) C/N ratio adjustment by mixing high carbon materials with high nitrogen materials at 2:1 or 3:1 (optimal C/N: 25-30 [38] or 20-50 [31]); e) adjustment of pH to optimal values of 6.5-8 [38] or 5.5-7.5 [31];

- Mixing: Different incoming feedstock materials should be stored in separate covered stockpiles: perishable high moisture materials (e.g. food waste) stored in aerated enclosed areas; bulking agents (e.g. sawdust, bark or even oversized compost components screened out from the final product). These materials are mixed in a way to adjust specific characteristics of the composting mass. The initial mixing is very important for closed systems. Ideally, pre-treatment, blending and mixing should be performed withn 24-48 hours from the time feedstock is received, to allow for a fast biomass decomposition and stabilisation.

Composting – Composting systems: The various composting systems operating in medium–to-large facilities may be categorized as follows [34,40,41]:

- Intensive/ extensive: The choice affects: investment /operational cost, operational experience /process management requirements, available options to achieve targeted product quality, processing different feedstocks / expanding processing capacity.

- Open/ enclosed technology: The technology adopted with open systems, closed stationary or agitated in-vessel systems affects emitted odour, bio-aerosols risk and leachate release, footprint (annual throughput, t/m^2) and utitilies used (energy, water). Closed in-vessel systems allow for a continuous regulation and optimisation of water content, temperature and oxygen concentration and the highest dust and odour control.

- Static/ dynamic: the organic material is handled as a continuous stream (dynamic method), or partially continuously (semi-static methods) or in a batch mode (static methods). The most widely used static system is the windrow composting process that uses mechanical turning to ensure increased periodic aeration [42,43]. This system combines low investment cost, simplicity in process control level, adaptability and flexibility, allowing for quality compost production. The static aerated windrow incorporates continuous forced aeration.

Composting - Active composting process: The composting process in any system, has two phases [38]:

- ***High-rate initial phase****:* Thermophilic temperatures and adequate aeration are required to produce a stable final compost that can be stored and used in agricultural applications. Thermophilic temperatures develop during the initial processing phase (following the first few days with mesophilic microorganisms activity) associated with high oxygen (O_2) supply/consumption and a high odour potential. Heat is produced by the biological activity (mainly bacteria) and thermophilic temperatures develop (higher than 50°C) for optimum (54 – 60 °C) thermophilic microbial action (thermophilic conditions prevail near the core of a static pile and mesophilic conditions with optimum microbial growth range from 20 to 45 °C in the external organic mass). Temperatures may climb even above 70°C under the combination of adequate oxygen availability and intensive microbial activity. During this process, high temperatures accelerate the breakdown of high energy compounds by microorganismsms, including proteins, fats, and complex carboydrates, such as cellulose and hemicellulose [44]. This results in rapid Biological Volatile Solids (BVS) decrease rates (i.e rapid decrease rate of the organic fraction of biodegradable components "destroyed” during treatment). The organic fraction of biodegradable components that remain after the treatment represents the Residual Volatile Solids (RVS). The “pasteurization” of the organic mass (disinfection or sanitization process) is ensured provided that the compost mass temperature is retained higher than 55°C for at least 3 days (e.g. temperatures ≥ 55°C for an extended period of 15 days, along with 5 turnings, optimized aeration and water content contol) [45]. Many human or plant pathogenic microorganisms, being heat-sensitive, are destroyed at temperatures over 65°C [44, 46]. Odours, developing as a result of anaerobic decomposition in the less aerated middle of the composting pile, are usually filtered out by the surrounding composting mass, functioning as an effective bio-filter [38]. Release of odours is unavoidable when the composting mass is turned, for better aeration and mixing, to adjust temperature and water content, or when aeration and O_2 supply are inadequate and anaerobic composting dominates the decomposition process.

- ***Secondary low-rate phase****:* The composting process continues at lower temperatures (mesophilic, up to 45°C) as some micro-organisms gradually become inactive or die. The decomposed organic mass is stabilized in this phase, BVS decrease at lower rates as compared to the intial phase and the odour production potential is reduced., Emmissions that need to be monitored and controlled during the active composting phase include: odour, dust and possibly leachate. Special emphasis is placed by Directive (EU) 2019/1009 [11] on the potential effect of additives used to improve the composting process and/or its environmental performance.

Post-treatment: The material produced during the active composting phase is further refined through screening to remove all remaining impurities (e.g. glass, ceramics, plastics etc.). Organic materials that need more time to degrade (sorted out through a sieving procedure) are recirculated back to the active composting process. The recirculated material replaces additional material (e.g. bulking agents) used as input to improve the structure of the incoming feedstock.

The refined compost has to mature in order to become a fully composted and stable commercial product. In the case of static composting systems, maturing partially occurs during the secondary low-rate active composting phase in the pile. In contrast, compost maturing is a critical phase for the compost produced quickly during the initial active composting phase in closed in-vessel systems. As the composting process is slown down, temperatures decline and the microbial community is adapted to the changing conditions but remains active following the progress of the maturing process at lower temperatures and limited amount of organic mass still available for decomposition. Continuous monitoring, aeration and hydration is needed through turning and wetting to sustain the microbial activity until the completion of the maturation phase. Environmental impact related parameters should also be monitored and controlled, aimed at: suppression of dust emissions; prevention of compost contamination by pathogens from feedstock or regrowth; management of effluents (e.g. leachate and stormwater) to avoid possible contamination of water bodies in the region with pathogens and/or pollution with nutrients.

Market: The main product of this process is the mature compost, while the byproducts include leachate, water and CO_2. The mature compost quality depends on the feedstock characteristics and the composting technology and processing. This product should meet the specifications of the Directive (EU) 2019/1009 [11] or the United States Department of Agriculture (USDA) organic regulations [47,48]. In particular, an EU fertilizing product, has to meet the requirements regarding [11]: a) functional category, including organic fertilisers and organic soil improvers (Annex I), b) component material categories, including compost produced from mixtures of bio-waste with biodegradable bio-based plastics (Annex II) and c) labelling (Annex III).

2.2.4.3 *Anaerobic digestion*

An alternative valorization route for bio-waste, and also for post-consumer /industrial biodegradable bio-based plastics characterized as non suitable for material recovery, is organic recycling through AD technologies. The bio-waste and other organic materials for AD processing should be collected separately, as in the case of bio-waste destined for aerobic composting processing, according to the requirements of standards and directives relevant to AD processing and Directive (EU) 2019/1009 [11]. Organic materials are broken down in AD facilities through a series of controlled and optimized natural biological processes by bacteria (especially methanogens and sulfate-reducing bacteria) in the (relative) absence of oxygen [49,50]. Some organic materials (e.g. post-consumer biobased plastics) that are biodegradable under aerobic conditions by fungi, may not be biodegrable under AD conditions by anaerobic bacteria. Organic materials suitable for processing under AD conditions include: municipal and industrial wastewater solids, industrial organic residuals, food waste, food processing wastes and byproducts, crop residues and crops for energy, fats, oils, grease etc. [49,51]. The main products of biodegradation of bio-waste under AD conditions are digestate (liquid and solid digested material), and bio-gas (50-70 % CH_4, 30-40 % CO_2, trace amounts of other "contaminant" gases) that may be upgraded into bio-methane [52,53]. The solid digested material is further processable into soil improvement compounds while the nutrients contained in the liquid streams may be processed and used as fertilizer. Emissions (e.g. NO and odours) are low [49].

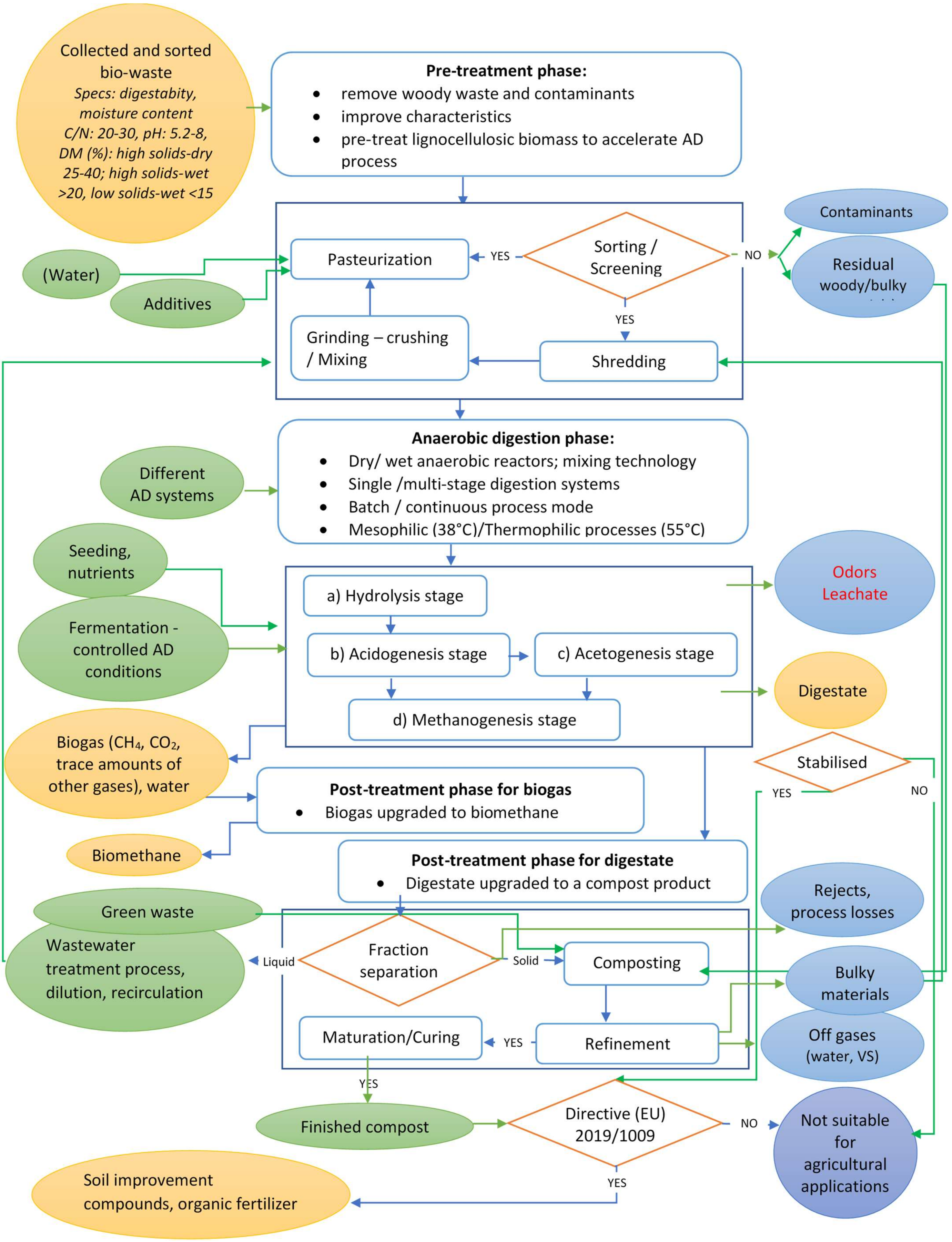
Collected and sorted bio-waste
Specs: digestabity, moisture content
C/N: 20-30, pH: 5.2-8,
DM (%): high solids-dry 25-40; high solids-wet >20, low solids-wet <15
Pre-treatment phase:
remove woody waste and contaminants
improve characteristics
pre-treat lignocellulosic biomass to accelerate AD process
(Water)
Additives
Pasteurization
YES
Sorting / Screening
NO
Contaminants
Residual woody/bulky
YES
Grinding – crushing / Mixing
Shredding
Anaerobic digestion phase:
Dry/ wet anaerobic reactors; mixing technology
Single /multi-stage digestion systems
Batch / continuous process mode
Mesophilic (38°C)/Thermophilic processes (55°C)
Different AD systems
Seeding, nutrients
Fermentation - controlled AD conditions
a) Hydrolysis stage
b) Acidogenesis stage
c) Acetogenesis stage
d) Methanogenesis stage
Odors
Leachate
Digestate
Stabilised
YES
NO
Biogas (CH₄, CO₂, trace amounts of other gases), water
Post-treatment phase for biogas
Biogas upgraded to biomethane
Biomethane
Post-treatment phase for digestate
Digestate upgraded to a compost product
Green waste
Wastewater treatment process, dilution, recirculation
Liquid
Fraction separation
Solid
Composting
Rejects, process losses
Bulky materials
Off gases (water, VS)
Maturation/Curing
YES
Refinement
YES
Finished compost
Directive (EU) 2019/1009
NO
YES
Not suitable for agricultural applications
Soil improvement compounds, organic fertilizer

Fig. 3. Schematic diagram of the anaerobic digestion processes

The AD processes are divided into 3 phases as shown in the schematic diagram of Fig. 3: a) pre-treatment, b) anaerobic digestion, c) post–treatment/refining of final products [34,54,42,55, 56, 35,57]. Several different AD systems and processing schemes are used, designed for various feedstocks and applications. The main stages and factors pertaining in the three phases of the AD processes (Fig. 3:) are briefly presented below:

Pre-treatment*:* Organic materials suitable for AD processing are selected based on their digestability under anaerobic conditions. Lignocellulosic materials need much longer time to break down. Materials with high lignin content (e.g. wood waste) cannot be digested by most anaerobic bacteria or without high temperatures pre-treatment. Energy crops are used especially for biogas production. Sewage sludge and manure have a low potential for gas production. Biogas production increases significantly in agricultural digesters through the use of different feedstocks mixtures (e.g. manure with grass or crop residues) in a co-digestion or cofermentation process [58,59].

- Separation: Physical contaminants removal (e.g. plastics, glass, metals) is important for wet feedstock digestion or plug-flow digestion facilities. In the case of dry feedstock digestion or solid-state anaerobic digestion (SSAD) facilities, removal of physical contaminants is not required for biogas production. It is important however for the digestate quality and its potential valorization [11]. The screened and sorted feedstock is usually shredded, and ground, crushed or slurried to increase the digestion rates through increased material surface area available to anaerobic bacteria. The clean organic material is “pasteurized” (many pathogenic microorganisms are heat sensitive and they are destroyed by temperatures above 55 °C) and pumped into the airtight digester.

- Improvement of characteristics: The feedstock composition affects significantly the CH_4 production rates and final yield. The feedstock moisture content affects several AD processing and design parameters: AD system, area and equipment, wastewater discharge. Dry feedstocks (e.g. food waste) are suitable for digestion in systems with higher energy demands for handling (e.g. tunnel-style digesters). Wet organic materials can be handled with standard pumps but require more space. Processing of dilute feedstocks (e.g. from food industry wastewater) in high-solids AD requires mixing with bulking agents (e.g. compost) to adjust the solids content (e.g. 40-60%). Optimal C:N ratio (20–30) and volatile solids (VS) to dry matter (DM) content ratio VS/DM>60%, required for AD processing, are achieved by mixing suitable substrates [60].

Anaerobic digestion – AD systems:

- Anaerobic reactors: The various anaerobic reactors can be categorized based on the Total Solid (TS) content (or DM) as follows [61,34]: a) solid state (dry digesters) for feedstock with TS>20% operating in continuous horizontal and vertical plug-flow (20-45%) or batch non-flow (30-40%); b) liquid state (wet digesters) for feedstock with TS<15% in suspended growth (TS<15%) and attached growth (TS<5%) [62].

- Anaerobic digestion systems: The AD systems can be categorised into [61]: a) single-stage digestion systems containing one reactor for all digestion steps; b) two-stage digestion systems containing two reactors for the hydrolysis/acidogenesis/acetogenesis and methanogenesis digestion steps, respectively; c) three-stage digestion systems containing three reactors for the hydrolysis, acidogenesis/acetogenesis, and methanogenesis respectively. The AD systems may employ wet or dry reactors in each stage. In single-stage reactors the parallel biological reactions of the four stages does not allow for achieving the optimal conditions required by the different species. Multistage systems allow for optimal conditions to be achieved for the bacterial communities activated during the first three stages in the first reactor(s) and the special conditions to be achieved and controlled for the most sensitive methanogenesis stage in the last reactor.

- Operation: AD systems may operate in batch or continuous process mode. The continuous process requires more sophisticated reactors design. The batch process requires more space and higher infrastuctures investment for the same amount of waste. Several reactors may operate in sequence with the continuous process. Operational cost is lower for batch process performed in a series of reactors for a continuous biogas production. Batch AD process may be associated with serious odour issues unless integrated with in-vessel composting following the completion of the AD process.

AD systems may operate the methanogenesis stage under mesophilic (20°C up to 45°C; optimum: 30-38°C) or thermophilic (up to 70°C; optimum: 49-57°C) temperatures. Thermophilic systems require more energy but allow for better pathogens reduction according to relevant EU Regulations and are more efficient in terms of biogas output and quality. Mesophilic systems are more stable.

Anaerobic digestion - Fermentation process: [61, 63]: The anaerobic digestion process involves a series of four bio-metabolic stages during which anaerobic microorganisms digest biochemically the organic substrate into CH_4 and CO_2: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

- ***Hydrolysis****:* The first stage consists of the hydrolysis of high molecular-weight (MW) complex organic compounds. Organic polymers (e.g. carbohydrates, proteins, lipids), are broken down by exo-enzymes through the bacterial hydrolysis into soluble low-MW derivatives such as sugars, fatty acids (FAs), amino acids. Optimum pH-values: 6-8 [64]. In the case of lignocellulosic materials, the overall digestion rate of enriched feedstock is limited by the slow hydrolysis process of lignocellulose [65]. The hydrolysis of the lignocellulosic biomass can be accelerated by means of biological or physical pre-treatment methods [66].

- ***Acidogenesis**:* During the second stage, sugars and amino acids are converted, by acidogenic bacteria, into CO_2, H_2, NH_3, and organic acids (e.g. volatile fatty acids (VFAs) such as propionic acid, butyric acid, acetic acid and ethanol). The process is sensitive to pH with optimum pH-values: 5.5-6.5 [61]. Acetate, CO_2, and H_2 produced in this stage can be used directly in the fourth stage by methanogens.

- ***Acetogenesis**:* During the third stage, most of the organic acids (VFA molecules with higher MW) and alcohols produced during the previous stage are catabolised by acid-forming bacteria (acetogens) into acetic acid and additional amounts of CO_2, H_2, NH_3, that can be used directly by methanogens. This process is strictly anaerobic with optimum pH-values: 6.0-6.2. Hydrogen produced should be released to the fourth stage to be consumed by methanogens as it is inhibiting the acetic acid formation [61].

- ***Methanogenesis**:* During the last stage, methane-forming archaea (acetotrophic and hydrogenotrophic methanogens) convert the intermediate products of Acidogenesis and Acetogenesis into the final product, biogas (CH_4 and CO_2 and trace amounts of other gases, e.g. H_2S) and water. The second AD product, the digestate, consists of the remaining indigestible organic material together with any dead bacterial biomass. The methanogenesis conditions should be controlled carefully as methanogens grow slowly and are very sensitive to changes in the processing conditions. Requirements include stable pre-defined temperature, absence of O_2, limited presence of inhibitors (e.g. free NH_3, H_2S, VFAs) and presence of macro- and micronutrients. Optimum pH-values: 7-7.2 ($6.2<pH<7.8$) [61]. Another important requirement is the efficient mixing of the substrate in the reactors during all stages to improve contact with the resident bacteria.

Post-treatment:

The quality of digestate, the organic fibrous residual material left in the reactors at the end of the AD process, varies. Digestate can be used as a low value product (e.g. landfill cover, landspread). Non-stabilised digestate upgraded through post-processing aerobic composting process together with green waste and following maturation, becomes a higher value product (e.g. soil conditioner /improvement coumpound or organic fertiliser) [63]. This post-treatment process aims at ensuring that the upgraded compost product meets the specifications of the Directive (EU) 2019/1009 [11]. Leachate after wastewater treatment is routed back to the pre-treatment phase re-circulating water, nutrients and microorganisms. Bulky materials sorted out during composting - screening are recirculated back to the pre-treatment phase for shredding and crushing.

Market: *Biogas:* Biogas, can be further upgraded into biomethane in two steps: a) trace components removing process (e.g. corrosive gases); b) calorific value upgrading process. The aim of biogas upgrading, or biogas purification, is the production of biomethane, or Renewable Natural Gas (RNG), an attractive alternative to natural gas. Biomethane, can be used as a pipeline-quality product gas in combined heat and power (CHP) systems generating electricity and heat [67]. *Digestate:* can be upgraded through aerobic composting process into soil improvement compounds. *Wastewater*: AD process liquid represents a major environmental problem for AD facilities. As this byproduct is enriched with anaerobic bacteria, nutrients and water, it may partially recirculated back to the incoming bio-waste. The recirculated quantity depends on the contaminants concentrations (e.g. heavy metals, N, P) and the applied wastewater treatment processes. The remaining leachate has to be handled according to relevant specifications.

3 TESA criteria and indicators

3.1 TESA criteria for organic recycling (industrial aerobic composting and anaerobic digestion) of bio-based plastics

The techno-economic sustainability criteria and indicators that are proposed to assure the technical feasibility and economic viability of organic recycling, as the second preferred alternative EoL option, for post-consumer /industrial biodegradable bio-based plastics characterised as mechanically/chemically non-recyclable [68,69], are presented and analyzed in the following sections. TESA criteria that are used also as environmental sustainability assessment criteria through LCA are included categorized as “common techno-economic – environmental” criteria. The recirculation potential criterion is presented for the purpose of underlining the significant difference of its importance between the first preferred EoL option of material recovery and the second option of organic recycling.

3.2 Industrial aerobic composting and anaerobic digestion feasibility TESA criterion

Biodegradability: Only non- recyclable bio-based post-consumer /post-industrial plastics that are biodegradable under industrial aerobic composting and/or AD conditions can be considered suitable for the organic recycling EoL option.

Bio-based plastics may have different biodegradation behaviour under aerobic composting and AD conditions. A material that biodegrade under aerobic composting conditions doesn’t mean that it will biodegrade also under anaerobic conditions. This behaviour can be attributed to the different nature of microorganisms present in aerobic and in anaerobic conditions. Fungi which consume the material in aerobic conditions, in combination with bacteria and actinomycetes, are absent in AD where the dominating microorganisms are bacteria that metabolize the organic material [53].

Proposed indicator: Main characteristics of post-consumer /post-industrial plastics allowing them to follow organic recycling EoL routes. Indicative qualitative indicators:

- *Biodegradable under industrial aerobic composting conditions (Yes/No)*
- *Biodegradable under anaerobic digestion conditions (Yes/No)*

Sorting efficiency: Recyclable bio-based plastics will be routed to material recycling under the TESA criteria presented in [70]. The provisions for the sorting process presented for mechanical and chemical recycling [70] apply also for organic recycling. In the case of mixed plastics waste streams, the sorting efficiency of non-recyclable from recyclable bio-based biodegradable plastics is critical during the waste management process. Separate collection of non-recyclable biodegradable post-consumer /post-industrial plastics is preferred (e.g. biodegradable plastic contaminated by organic residues), as it is also required for municipal bio-waste routed to organic recycling. Since the addition of bio-based plastics to biowaste is ideally accompanied by a more intensive communication and education campaign about source separation, it will reduce the level of contaminants in bio-waste and it will boost the addition of non-recyclable biodegradable bio-based plastics in organic recycling systems.

Aerobic composting facilities: When aerobic composting is to be considered, the sorting efficiency of post-consumer bio-based compostable plastics rejected from recyclable mixed plastics waste streams, is a critical requirement for the smooth operation of the composting facilities. The uniformity of the sorted non-recyclable post-consumer compostable bio-based plastic stream affects the acceptance of the stream routed to the composting facilities and allows for the composting option to be attractive for bio-based plastics. The quality of both, the sorted compostable plastics and the bio-waste can be enhanced significantly by applying separate collection of bio-waste [1, 2,71].

AD facilities: The role of sorting in the AD treatment option is crucial as well, as the feedstock for the AD should be of high quality in order to ensure stable operation of the digester [72]. However, the behaviour of bio-based plastics under AD conditions should be further investigated as little information exist. Not all certified compostable bio-based plastics will degrade to the same extent under AD conditions. Also, the same bio-based plastics, may perform differently under different AD technologies. The need for more systematic research on this subject, in combination with the lack of standard specifications, certificates or labels for anaerobic digestibility of bio-based plastics, underlines the problem in source separating the digestible bio-based plastics.

The sorting efficiency of bio-based plastics for organic recycling is a measure of the quantity of the biodegradable post-consumer bio-based plastic stream sorted out from the initial quantity of the collected plastic waste streams and characterised as non-recyclable, or from separate collection schemes for biodegradable bio-based plastics. The sorting efficiency is calculated by combing the sorting yield (%) (accounting for missed targeted material) with the purity (%) of the sorted material (obtained by methods like NIR and manually). Proposed quantitative indicators for aerobic composting and AD, η_{sort} = sorting yield (%) x purity (%):

Aerobic conditions:

- *η_{sort} (%) = mass of sorted pure biodegradable, under aerobic industrial conditions, post-consumer bio-based plastics (kg) x100/ mass of the collected non-recyclable post-consumer bio-based plastics or separate collected post-consumer biodegradable bio-based plastic streams (kg)*

AD conditions:

- *η_{sort} (%) = mass of sorted pure biodegradable under AD conditions post-consumer bio-based plastics (kg) x100/ mass of the collected non-recyclable post-consumer bio-based plastics or separate collected post-consumer biodegradable bio-based plastic streams (kg)*
- *Note: all measures of quantities /mass (kg) in the present work are defined on a dry weight basis.*

Biodegradability/ Compliance with standards: The technical feasibility of organic recycling relates to the conformity of bio-based plastics to the compostability and/or digestibility requirements defined by standard specifications so as to be accepted for industrial composting and/or AD. The situation is clearer in the case of industrial aerobic composting compared to that of AD.

For **the aerobic composting**, the materials that are directed to the composting facilities need to meet the criteria of the European norms EN 13432 [73] and EN 14995 [74]. Compostable packaging and plastics can be defined as packaging and plastics which, when introduced into an industrial composting plant together with the main stream of organic waste, are biodegraded and bring no inconvenience neither for the process nor for the product and the environment. Four basic compostability criteria are specified by EN 13432: material characteristics, disintegration, biodegradation, and ecotoxicity. Other relevant standards and regulations to be considered in the EU include PPWD [25,75] and the fertilising products Regulation [11]. Equivalent international standard specification for industrial compostability include ASTM 6400-19 [76] and ISO 17088 [77]. Compostable plastics that meet the criteria of compostability set by the European norms EN 13432 and EN 14995, or other equivalent standard specifications, are certified and labelled by independent certification organizations such as DIN CERTO [78], TUV Austria [79], GreenPla Japan [80], etc.

Standard test methods are used for the determination of the aerobic biodegradation of plastic materials in the laboratory under controlled composting conditions through respirometric methods [81,82, 83]. According to [84], the standard test methods for biodegradation of bio-based plastic may fail to evaluate the composting performance under realistic composting conditions. This refers mainly to tests (e.g. according to the ASTM method [81]) that use as inoculum only mature compost. Mature compost, however, may affect the activity of the microorganisms responsible for the biodegradation of the bio-based plastics by withholding nutrients and by influencing the pH [85]. The addition of organic waste to the compost inoculum (e.g. raw food), could result in a better simulation of the actual composting process stages [84]. It has also been suggested that inter-laboratory biodegradation tests under composting conditions should be performed with different standardized reference materials, strictly controlled inoculum characteristics (using compost and/or vermiculite) and testing parameters aimed at the harmonization and improvement of the existing test methodology [86].

For the **anaerobic digestion** option, the technical feasibility should relate to the conformity of bio-based plastics to the biodegradability under AD conditions requirements, defined by standard specifications. The current situation is characterized by the lack of such standard specifications though. This represents a major barrier for the development of AD [9]. In contrast, several standard test methods have been developed to determine the degree of biodegradation of plastics under anaerobic conditions simulating AD plants. Some relevant standard specifications include: ISO 20675:2018 [87] and a Publicly Available Specifications (PAS), BSI PAS 110:2018 [88,89]. Biodegradation test methods [90]: EN ISO 15985:2017 [91] and ASTM D5511:2018 [90,92] (under high-solids AD conditions), ISO 13975:2019 [93] (controlled slurry digestion systems), ISO 14853:2016 [94] (aqueous system).

Proposed indicator: Technical feasibility for aerobic composting and/or AD of sorted non-recyclable post-consumer bio-based biodegradable plastics according to standard specifications. Indicative metrics are:

- *Compliance with standard specifications for compostability under industrial aerobic composting conditions (Yes/No)*
- *Compliance with standard specifications for biodegradability under AD conditions (N/A)*

A synoptic presentation of research works on the biodegradation behaviour of various bio-based polymers, plastics, blends and bio-composites under aerobic industrial conditions and AD conditions is presented in the following section and in *Table 1* and *Table 2*.

3.3 Performance of bio-based plastics in organic recycling

The performance of specific bio-based plastics has been investigated under various laboratory and pilot scale composting and AD conditions. A few review papers present the biodegradation behaviour of various bio-based plastics under different organic recycling conditions [95,96,97, 98].

3.3.1 Performance of bio-based plastics under aerobic composting conditions

A Synoptic review of literature on the biodegradation of bio-based polymers under industrial aerobic composting conditions is presented in Table 1. Among the most studied materials are PLA, PLA-based blends and composites, starch-based polymers and PHAs. The biodegradation behaviour of PLA under solid state aerobic composting conditions (as well as under aquatic conditions) was shown to be regulated predominately by the temperature [90]. Biodegradation of PLA starts following the beginning of the thermophilic phase in both compost and anaerobic treatment facilities. The disintegrability of PLA caused by fungi and bacteria under aerobic composting conditions starts when the molecular weight of PLA is reduced through down to 10000-20000 g/mol [99]. The results reported show very slow hydrolysis associated with 10% biodegradation at temperatures below 37 °C in 7 weeks [90]. The PLA polymer hydrolysis, involving water uptake, ester cleavage, and formation and dissolution of lactic acid and oligomers, allows the microorganisms to consume them as a nutrient source. Hydrolysis is enhanced by high temperatures (PLA T_g: 55 - 61 °C) and elevated water content. High degrees of PLLA biodegradation under aerobic composting conditions reported in the literature are mainly related to high incubation temperature at 58 °C, rather than the nature of the compost (biomass used, assuming natural communities of microorganisms and proper composting conditions) [100]. The degree of biodegradation also depends on specimen' morphological structure and the polymer's degree of crystallinity. The degree of disintegration of neat PHB films in composting conditions was shown to reach only 1.5% after 35 days [101]. The addition of plasticizers resulted in an increase of the degree of disintegration. Other research results however, report that neat PHB will be disintegrated in compost in approximately 6 weeks [102].

Table 1. Synoptic review of literature on the biodegradation of bio-based polymers under industrial aerobic composting conditions

Material	Aerobic Composting processing conditions	Biodegradation behaviour	Reference
PLA			
Poly-L-lactide (PLLA) (T_g *55°C*; M_w*130000 g/mol*) [103]: nonwoven fabrics (M_w *75000),* blown film (*30 µm*, M_w*: 100000*) (low % lactide monomer; no additives)	Fabric *5.2% (w/w)*, film: *2.9% (%)*; Samples mixed with the bulking material, Biowaste: vegetables, fruit waste Continuous aeration at *4 l/min*, turned weekly *Thermophilic phase 70°C* in less than 10 days	Temperature rise, CO_2 generation higher in composts containing PLLA samples due to higher microbial degradation activity; PLLA mineralisation: fabrics: 40 days, no lag phase; films: 20 days after lag phase; all PLLA samples: maximum after 40 days, followed by decreased compost mineralisation degree mainly from bio-waste; Final PLLA mineralisation degree films 99%; fabric: 73% and 48%; reference paper: 94%	[90]
Ingeo™ 2003D [104]: (*4.25% D-lactide;* M_w *112,000 g/mol*) Films (*22-34 µm*) PLA1 (M_n *93.5 kDa*), PLA2, (M_n *82.9 kDa*), PLA3 (M_n *72.6 kDa*); Ingeo™ (4032D): (*2% D-lactide*), PLA4 (*255 µm*) (M_n *75.0 kDa, amorphous*)	Film samples: *8 g* in 500 g or 400 g (wet wt.) of compost or 400 g of inoculated or uninoculated vermiculite; *58 ± 2 °C, pH 7*. Continuous aeration at *40 ± 2 cm*^{3}*/min*;	Biodegradation of pellets (day 60 days): 39.2±5.5% in compost; 34.5± 2.8% in incubated vermiculite Biodegradation of films in compost: Lag phase: 20 days; Degree of biodegradation (day 60): PLA1: 63.3 ± 6.78%; increased as M_w decreased; PLA2: 67.6 ± 7.1%; PLA3: 91.5± 7.0% Max degree of biodegradation: PLA3: 109.1% (due to priming effect); PLA4 >100% Biodegradation of films in incubated vermiculite: Lag phase: 20 days; Degree of biodegradation (day 60): PLA1: 34.6%, PLA2: 58.3& same as in compost; PLA3: 48.5% (similar to PLA1, PLA2) No significant biodegradation for samples tested in uninoculated vermiculite	[86]

PLA Ingeo™ (4032D) (*2% D-lactide, M_n 107000 g/mol*) [104], PLA filled with functionalized anatase-titania nanofiller (PLA/TiO_2 nanocomposites *(0-15 wt% G-TiO_2)*)	Biowaste: organic fraction of MSW sieved to sizes under 5 mm (pH 7.2, TS 71.3%, VS, 19.3 % TS, RAC 80.7 % TS, Moisture 53.5 %, C/N 15 Samples and reference microcrystalline cellulose (MCE: *15 g;* bio-waste: *85 g* and *320 g* of dry sea sand Temperature: *58°C*, aeration: *25 ml/min*	Biodegradation: higher for PLA/TiO_2 nanocomposites because water molecules penetrated the nanocomposites easily; rapid increase of crystallinity. Hydrolysis related changes with degradation time: *Tg*: slight decrease, T_{cc}: disappearance in 2 days; T_m: decrease due rapid M_n reduction. Degree of biodegradation: MCE: starts after 5 days, 72% in 45 days; PLA and PLA/TiO_2: lag phase of the nanocomposites was a little shorter than that of pure PLA, 78.9% (PLA) - 85.0% (*15 wt% G-TiO_2*) in 80 days.	[105]
Commercial PLA lids, Biobag trash bags, Ecoflex Polyester bags, PHA Bags, Husky Eco Guard biodegradable bags, Sugar Cane Bagasse lids Reference: Kraft paper, polyethylene plastic bag	Aerobic composting: Degradation: In-vessel (Food Waste Compost); Disintegration: Windrow (60*°C, moisture: 40-45%)* Visual disintegration and biodegradation of products: 30, 60, 90, 180 days Lab: 58°C, 100 g of plastic with 600 g of mature compost (ASTM 5338)	Degradation in vessel (commercial food-waste composting operation; 30d): Some degradation: Food waste, PLA articles, Sugar cane plates and lids, and Biobag trash bags Disintegration Windrow (180d): full disintegration: PHA bag, Ecoflex bag, PLA lids, Husky Eco-Gu and TPS plastic trash bags; high disintegration: Sugar cane lids and Kraft paper control; Biodegradation (laboratory: ASTM 5338, 180d): PLA, sugar cane, PHA, Ecoflex, and starched-based biobag > 90% (ASTM D-6400).	[98]
PLA bottles (500 ml) Ingeo™ PLA [104] (*96% L-lactide); TOC: 49.5%, M_w 230 kDa)* blue tone additive	Real composting conditions: Compost pile (cow manure, wood shavings, and waste feed): 6m x 24m x 3m´ At 65*°C*, moisture: 63%, pH 8.5; bottle samples: entire bottle vs. (0.01x0.01 m^2) in simulated composting method; (30d)	Disintegration of bottles: pieces (15d), disintegrated (30d); M_w *<15 kDa* (15d) Biodegradation for PLA bottles (58d): 84.2% and 77.8% for (A) and (B) simulated composting methods Max allowed PLA in compost: 10% (w/w) to avoid acidification due to LA formation during hydrolysis	[106]
PLA, PLA-foaming agent, and PLA with 10 wt.% of corn (PLA-corn) [107].	Compost: solid biodegradable synthetic material (3 months mature); 58 *°C* for 90 days, TS 41-45%, VS 88.7%, C/N: 32.5, Samples (2% wet wt)	Degree of biodegradation (EN 14806, ISO 20200), (90d). PLA, PLA-F: 64%. With regard to the pieces made of PLA-corn: 80%; Disintegration of PLA lower than for foamed-PLA.	[108]
PLLA (M_w *175000 g/mol,* T_g 61°C, T_m *165*°C, cristallinity 32%.) [109]), Cellulose material: positive control	Inoculum: fungal consortium used to inoculate compost; concentration of 2x10^5 cells/ml; Composting: 58°C, 230d; second biodegradation test on the	Degree of biodegradation (58°C): cellulose: 90% (90d); PLLA: first phase; short PLLA chains available (0d-6d); deceleration: hydrolysis process (6d-19d): significant increase – plateau: 90% (90d); Second test at The biodegradation test (37°C): lag time, followed by a very slight bioassimilation:	[100]

	same materials in sterilized and inoculated compost at 37°C	5% (50d) (hydrolysis)	
PLA pellets (Cargill Dow): powdered PLA Tg: 61 °C.	Compost extract from a green compost (agricultural and tree wastes); composting inert solid medium: increased vermiculite, mineral solution, compost extract and one activation dose (starch, urea, cellulose, nutrients); 58°C, pH = 7.2, water content: 70%, shaking Degradation test duration: 45 d	Degree of biodegradation in solid inert medium (45d): 20% << 55-75% in real compost conditions (45d); Mineralization: very low (2 weeks, hydrolysis); increased significantly (13, 14d following M_w decrease, release of oligomers); protocol for carbon extraction and quantification in different degradation by-products, carbon balance of the polymer degradation during the test	[110]
PHAs			
PHBV (hydroxyvalerate (HV: 3 mol%) (viscosity-average molecular weight M_v *=300000 g/mol*) [111]	Pilot-scale composting conditions (ISO 16929): synthetic compost, film samples 10x10 cm^2 in 200 l steel vessel for 12 weeks; Lab-scale composting (ISO 14855); 58 *°C, WC of the mixture adjusted at 90% of WHC, 10g sample/550 g compost*	Pilot-scale composting: T_{max} *73 °C in 3d, 60 °C* after *4d* degradation, >*.40 °C* for *35d*; *pH: 6.4 – 8.8*, PHBV film completely disintegrated in 39d. No residual PHBV film fragments after 12 weeks Laboratory-scale: degree of biodegradation (35d): PHB (reference) 80%, PHBV: 81%	[112]
PHB (M_n *240000 g/mol*), PHBV (40 %mol HV) (M_n *324000 g/mol*), PHBV (20 %mol HV) (M_n *324000 g/mol*), PHBV (3 %mol HV) (M_n *404000 g/mol*) and (3HB,4HB) (10 %mol 4HB) (M_n *446000 g/mol*) [111]	Commercial compost from municipal organic waste (2 months mature); 58 *°C* TS: 52.4%, VS: 14.5%, pH: 8.2, C/N: 14.1, air supply: 150 ml/min (ISO 14855-1):	Decrease of M_n: PHB: 24.6% PHBV-3: 48.3%, PHBV-20: 51.5%, PHBV-40: 55.6%, P(3HB,4HB): 77.4%, Degree of biodegradation (ISO 14855): all materials and cellulose started degrading after 5d; PHBV-20 highest rate in 15d. All samples reached plateau after 70d. Ultimate degree of biodegradation (110d): PHBV-40: 90.5%, PHBV-20: 89.3%, PHBV-3: 80.2%, P(3HB,4HB): 90.3%, PHB: 79.7%; Cellulose: 83.1%. Degrees of biodegradation of all samples relative to cellulose P> 90% (ISO 17088): all materials are characterised biodegradable materials. Difference in biodegradability of PHAs due to decrease of crystallinity with the increase of HV and 4HB content	[113]
Mater-Bi			
Mater-Bi® [114] (commercial bioplastic carrier bags, BCB)	Compost heaps (25 kg): samples 7g/kg compost; evaluation: 10d (end of the	Disintegration rate: highest during the thermophilic phase after 10d; degradation rate during maturation phase: stable 10d, linear decrease until 55d: 70-80%	[115]

	thermophilic phase), 25d, 40d, 55d, end of test; first 10d:.up to *60°C*		
Mater-Bi (MB) [114] (starch derivatives ≥ 60%) Cellulose filter paper (CFP): positive control.	Compost: kitchen waste, yard waste, paper); C/N 27.9, moisture 55%, T_{max} *63°C* (5d), T >50*°C*: 3d, stabilised *30°C:* 10d; VS 92%; pH 6.5:(1d) - 8.5 :(40d)	Disintegration rate: CFP: 100% 72d; MB: 26.9% 72d	[116]
Mater-Bi (MB) [114], commercial BCBs	Mature compost with a content of total carbon of 42%; No information about standard test method and conditions	Disintegration rate (90d): 43%; Mechanical properties change: tensile strength: -69%; elongation at break: -68%	[117]
Starch-based			
Thermoplastic starch (TPS) and thermoplastic dialdehyde starch (TPDAS); TPDAS carbonyl content (%): 6, 30, 50, 70, 95; Microcrystalline cellulose: reference substance	Mature compost from organic municipal solid waste (ISO 14855) TS: 49%; VS: 28.38% (TS); pH 7.2; C/N 14	Degree of biodegradation (45d: microcrystalline cellulose: 74.05% TPS, TPDAS6, TPDAS30, TPDAS50, TPDAS70, TPDAS95: 73.11%, 65.91%, 55.52%, 45.12%, 25.60%, 6.079% (56 days); biodegradation rate decreased with the increase of the degree of oxidation of TPDAS; lag phase: different for TPDAS with varied carbonyl content	[118]
Starch-based plastic (from potato almidon); painted and non -painted (water paint)	Compost: commercial solid biodegradable synthetic material (EN 14806), 90d.: moisture:55%, 58*°C,* Moisture, mixing-aeration, periodically controlled, TS:47%, VS:92%TS, pH 7.0, C/N:30.3	Degree of bio-disintegration: painted samples: 84.6%, non- painted samples: 89.4%; painting: negative influence:-4.5% (paint acts as a barrier)	[119]
Blends of bio-based polymers - copolymers			
Commercial PLA, Synthesised PLA, Lactic acid, ethylene glycol, malonic or succinic acid copolymers: LA-EG-MA) and (LA-EG-SA)	ISO 14855-1:2005. organic fraction of approximately 3-month-old mature compost obtained from organic domestic; *pH 7.7, TS 50%, VS 29%,* moisture *55.6%, 50°C, 110 d*	Biodegradation (ISO 14855): reference material (MCE) > 70% after 45 days =valid tests Microcrystalline: Degradation start (after 5d); PLA samples: Induction period (0-10d): PLA hydrolytic degradation, M_w decrease. Biodegradation period (10d-90d): polymer chains broken into oligomers consumed	[120]

		by microorganisms; plateau phase (90d-110d): end of test Ultimate degree of biodegradation: PLA-1: 72%, PLA-2: 69%; copolymers with high percentage of LA: 69%, 69%; copolymers with low percentage of LA: 37%, 33%. End of test (110d), ISO 14855-1: MCE reference material: 76%. Relative biodegradation compared to MCE: PLA: 94% (1), 90% (2); copolymers with high percentage of LA: 90%, 90%; copolymers with low percentage of LA: 48%, 43% (strongly dependent on LA content)	
PLA (*10% D-lactide; M_w 150 kDa*) [104]; PHB (P209, *M_w 500-800 kDa)* [121]; Ecoflex F Blend C1200 (*M_w 40* kDa) [122]; Blends PLA/PBAT (50/50). PHB/PBAT (50/50); Films 35µm	Composting (ASTM D5338): Mature compost; moisture *47%, 55°C* Film samples 100gr mixed into the 1:6 ratio of the compost. Cellulose filter: positive control. Disintegration test: strips of samples	Disintegration: PHB in 10d > PLA, blends with PBAT (30d-45d); Degree of biodegradation (28d): PHB 80%, > PLA 70%, (lag phase - hydrolysis, biodegradation); blends lower degree of biodegradation (45%-50%) (selective degradation, formation of PBAT rich 3D porous network). PLA and PHB phases in blends with PBAT: higher rate of degradation	[123]
PLA Ingeo™ (4032D) (2% D-lactide, *M_n 217000 g/mol*) [104], PHB (P226, *M_w = 426,000 g/mol)* [121], PLA–PHB (75:25)-LIM (15%); D-limonene: *(M_w = 136.24 g/mol)*	Composting conditions (ISO 22000); biodegradable synthetic wet waste; *58°C;* air circulation; 35d	Degree of disintegration: Formulations without PHB: >90% (28d) (amorphous PLA); PLA–PHB: 12% (21d), 50% (28d), >90% (35d) (crystalline phase of PHB); Neat PHB: 1.5% (35d). Films with D-limonene: higher rates: PLA–PHB–LIM: 24% (21d), >90% (28d)	[101]
TPS combined with biodegradable polyesters, PLA blended with PBAT, PBAT	Multiple study on the compostability performance of plastics certified according to EN 13432 in various industrial aerobic composting facilities	Degree of disintegration: most materials < 3 months; performance depends on type of facility and material thickness	[124]
PLA Ingeo™ (4032D) (1.4% D-lactide, *M_n 112000 g/mol*) [104], PHB Biomer® (crystalline 65-70%) [121], Plasticizer triacetine (TAC)	Polymer samples (50 mg), mature compost from municipal composting facility (EU legislation): 58 °C	Degree of biodegradation (100d): PLA, PLA+TAC: ~ 90%, PLA/PHB+TAC > 90%; Start of disintegration: PLA (*M_n 30000 g/mol*): 10d, PLA+TAC (*M_n 25000 g/mol*):8d, PLA/PHB+TAC (*M_n 35000 g/mol*): 8d	[125]
Bio-based composites			

Ingeo™ 4032D (*2% D-lactide*) (*M_n 217 kDa*) (PHB Biomer, P226, M_w=426 kDa, [104]), (PEG, M_n =300 g/mol, acetyl-tri-nbutyl citrate (ATBC, M=402 g/mol; films *(200 µm*: neat PLA, PLA-PEG, PLA-ATBC, PLA/PHB-PEG, PLA/PHB-ATBC)	ISO-20200, solid synthetic bio-waste mixed with water: *45:55; 58°C for 35 days*; aeration: gentle mixing.	Disintegration: started in amorphous phase: loss of transparency, increase of crystallinity (addition of PHB in the structure: decrease in degradation rate; disintegration rate after 28 days: PHB/PLA blends visible, PLA completely disintegrated; neat PLA the only sample with no apparent visual changes in 7d; Disintegration rate after 21 days: PLA/PHB-ATBC: up to 65%, PLA/PHB-PEG: below 50%, plasticized PLA >85% (PLA-PEG > PLA-ATBC), net PLA ~ 80%; Weight losses: all samples > 90% after 28 days	[126]
Ingeo™ 2003D (*4.25% D-lactide, M_n= 210000 g/mol*) [104]. PLA bio-nanocomposite films (BNCs: 5% organo-modified montmorillonite (PLA-OMMT5), 0.4% surfactant (PLA-QAC0.4))	Biodegradation in compost, inoculated vermiculite with compost mixed culture and uninoculated vermiculite Conditions compost: *58°C,* moisture ~50%, TS *51.8%,* VS *41.3 %*, pH *7.9*, C/N *9.9* Bioaugmentation: *Geobacillus*	Biodegradation: PLA-OMMT5 and PLA-QAC0.4: shorter lag times (15d) than PLA (20d); biodegradation: slower in inoculated vermiculite than in compost; PLA-QAC0.4: priming effect in compost media; in uninoculated vermiculite: no biodegradation *Geobacillus*: accelerated biodegradation phase of PLA and BNCs when tested in compost and inoculated vermiculite with compost mixed culture: Shorter lag phase with the presence of Geobacillus	[127]
Ingeo™ 2003D (*4.25% D-lactide, M_w= 162000 g/mol*) [104]. PLA / potato starch blends (10:90, 25:75, 50:50, 75:25, 90:10)	Multi-purpose commercial compost (manure bedding, grass/leaves trimmings, wood wastes and municipal food waste) Conditions: 45°C and 55°C; samples 3cmx1cmx2mm in 5g of compost; 14 and 28 days; moisture: 40%. The effect of lipase addition was studied	M_w (compost, 45°C, 14d): Neat PLA: from *162 kg/mol* to *128 kg/mol*. All polymers except starch showed in FTIR strong absorptions in C=O stretch vibrations region at 1751-1760 cm^{-1} (carbonyl group). The bands for C=O group of the polymers in compost shifted to 1756-1759 cm^{-1} (without lipase) and to 1759-1761 cm^{-1} and 1762 cm^{-1} with addition of 10 mg (45°C) and 20 mg (55°C) of lipase, respectively, reflecting a M_w reduction. Generated CO_2: highest for pure starch (45°C no lipase), followed by the blends (enhanced degradability with increased starch) Lipase (15d): 10 mg (45°C): double CO_2 generation than that with no lipase; 20 mg lipase(55°C) decrease of CO_2 generation (lipase may not be so active at 55°C). Compost pH increased due to degradation (highest for starch)	[128]
PLA nanocomposite films: PLA fibers (1.25 g cm^{-3}, 6 mm length) [129] and cellulose nanocrystals (CNC) (length: 180 nm, diameter: 4.9 nm, 1-3% wt), unmodified (CNC),	ISO 20200, PLA and PLA nanocomposite films 15x15x0.03 mm^3 in solid synthetic organic substrate at 58*°C,* 50% humidity, daily mixing,14 d	Disintegration (ISO 20200 [130]): all the materials > 90% after 14d. PLA_3s-CNC film more breakable than the other samples in 3d In 7d: PLA_CNC: *30-40% weight loss,* PLA_s-CNC: *70% disintegrability* Temperature=*58 °C*: higher than T_g of nanocomposite and the surfactant presence increase chain mobility.	[99]

with commercial surfactant (s-CNC).			
PLA-limonene films reinforced with cellulose nanocrystals (CNC): PLA 3051D (*1.25 g cm^{-3}, M_n 14200 g/mol, MFI 7.75 g 10 min^{-1}*) [104]; D-limonene (*M_w = 136.24 g/mol*): 15, 20 or 25 wt.% (natural plasticizer), CNC: 1 or 3 wt.%: (e.g. 3 wt.% CNC): (PLA_20Lim_3CNC)	Nanocomposite films 15x15x0.05 mm^3 in solid synthetic organic substrate at 4–6 cm depth in perforated boxes (ISO 20200): 58*°C,* 50%, aerobic conditions.	Disintegration: hydrolytic degradation started (3d): whitening, surface deformation; fragmentation, weight loss (7d): all the materials: (7 d): PLA_20Lim, PLA-Limonene-_CNC: 25%; PLA_CNC: 20% Disintegration (10d): neat PLA and PLA_CNC: deep fractures (hydrophilic nature of CNC); less evident in limonene-based formulations (due to migration); Disintegration (14d): all materials >90% (ISO 20200) FTIR: decreased intensity at 1260 cm^{-1} (C-O stretching), completely disappears (14d) days in composting (depletion of LA and oligomers by microorganisms); decreased intensity at 1300 - 1000 cm^{-1} (PLA matrix) (7d-10d) due to the scission of PLA links (hydrolysis)	[131]
Ingeo™ PLA 7000D *(4.25 D-lactide)* [104] compounded with high-amylose cornstarch (20 µm), and wood-flour (500 µm): PLA/starch: 60/40, 90/10	Mature commercial compost (aged 2-3 months) (pH 8.4, TS 46.4%; AS ISO 14855). Specimens - injected moulded (10 mm x 20 mm x 3 mm) mixed with the compost in a vessel	Biodegradation: Reference material (cellulose): started immediately; degree of biodegradation > 70% in 40d (AS ISO 14855: reference material > 70% in 45d)→confirmation of test validity. PLA60/starch40: started immediately; degree of biodegradation: 50% in 40d, >80% in 80d. PLA90/starch10: lag phase 15d; degree of biodegradation slower, 60% in 80d. PLA/wood-flour: lag phase 15d; degree of biodegradation: 50% in 80d Decrease in pH (from 8.4 to 6.0) following biodegradation.	[132]
Ingeo™ PLA 2003D (4.5% D-lactide, *M_n= 210000 g/mol*) PLA, PLA + Clay1 (modified montmorillonite), PLA + Nano-CaCO$_3$, PLA + Nano-SiO$_2$.	Commercial compost (4 months mature; Biodegradation test ISO 14855:2012); Disintegration in solid synthetic waste (ISO 20200:2004); samples 100 g (10% pieces, 90% ground; dry w/w); 58*°C, water content:* 55%, periodic mixing for aerobic conditions	Disintegration (ISO 20200) (lab): PLA: 6 weeks; incorporation of nanoparticles did not hamper complete disintegration in the same period (slight delay: PLA-Nano-SiO$_2$). Degree of biodegradation (ISO 14855-1): cellulose: > 70% (45d); Lag phase: PLA (17d), PLA+ Clay1 (9d; high hydrophilicity), Nano-CaCO$_3$ (11d), Nano-SiO$_2$ (16d); rate of biodegradation: PLA + Nano-CaCO$_3$: fastest (30d-60d; shorter lactic acid oligomers); End of test (130d): PLA + Clay1 and PLA +Nano-CaCO$_3$ > 90%. PLA+ Nano-SiO$_2$: 80%, PLA: 75%.	[133]
PLA (Biomer L 9000, *M_n= 218000 g/mol*); injection moulded composites with fillers (M_n decreased by 20–39% with processing):	Composting (ASTM D 5338): commercial mature compost; 50 g of ground test materials in 700 g of compost. *58°C, C/N:30* constant supply of humidified CO$_2$-free compressed air.	Degree of biodegradation: Cellulose powder (reference) > 70% in 45d. Soy, wheat straw: >70 within 45d (ASTM D 6868). Composite materials: 90% in 70d (similar rates independently of biomass; reduced M_n) > PLA; PLA 90% in 100d. Degradability of PLA in natural fiber composites is enhanced compared to neat PLA	[134]

PLA-wheat straw (70:30) and PLA-soy straw (70:30)		(ASTM D 6400)	
Ingeo™ PLA 2002D Composite with and without maleic anhydride (MA), TPS (corn starch) and short natural fibre (coir); PLA/TPS composite 75/25	Compost: mature compost (2 mo) from vegetable refuse; Moisture 52.4 %, VS 45.4%, pH 7.1, C/N 10.4, TOC 17.2%	Degree of biodegradation (90d): TPS 87%, PLA: 55%, PLA/TPS: 61%, PLA/TPS/coir composite: 59%, PLA/TPS//MA (combatibilised matrix): 57% compatibilised composite (PLA/TPS/coir/MA): 54%; TPS: no lag phase, max rate of biodegradation: 0d-20d, plateau: after 40d; PLA: lag phase: 12d, max rate: 12d-50d linear increasing phase, plateau: after 70 d; Blend PLA/TPS (standard matrix): no lag phase, linear increase phase, plateau 50d; Composites similar behaviour as the blend PLA/TPS	[135]

3.3.2 Performance of bio-based plastics under anaerobic digestion conditions

A Synoptic review of literature on the biodegradation of bio-based polymers under AD conditions is presented in Table 2. Natural PHA polyesters (e.g. PHB, copolyester PHBV) were shown to biodegrade in various anaerobic media. However, their biodegradation rates are different (PHB>PHBV) than those observed under aerobic composting conditions (PHBV>PHB). Thermoplastic starch (TP) was shown to biodegrade under AD conditions like PHAs [136]. Synthetic polyester PCL showed slower biodegradation rates than PHAs while PBAT-copolyesters showed limited or no biodegradation under AD conditions. PLA was shown to biodegrade under thermophilic AD conditions but shows limited biodegradation under mesophilic AD conditions. In the case of mesophilic AD conditions PLA may biodegrade under the subsequent last phase of high temperature aerobic composting for the stabilisation of the digestate. In general the biodegradation order of bio-based plastics in biogas plants was shown to be: PHB > PCL > PLA > PVA [96]. PCL, PLA and PVA take longer than the hydraulic retention time (HRT) applied in biogas plants. PBS does not biodegrade under AD conditions of biogas plants.

Table 2. Synoptic review of literature on the biodegradation of bio-based polymers under anaerobic digestion conditions

Material	Anaerobic Digestion processing conditions	Biodegradation behaviour	Reference
PLA			
Poly-L-lactide (PLLA) (T_g *55 °C*; M_n *130000 g/mol*) [103]: nonwoven fabrics (M_w *75000),* blown film (*30 µm*, M_w *100000*) (low % lactide monomer; no additives)	*Aquatic anaerobic test (ASTM D 5210)*, *37* °C *Anaerobic solid state digestion test (ASTM D5511, CEN Draft):* PLLA samples: *3–5 g*, inoculum: *300 g* at *52 °C*, mixed weekly	Biodegradation of PLLA; faster at *52°C* than at *37°C* Mineralisation degree at *52°C:* PLLA 60% in 40 days; Positive control Biopol (PHB) (*52°C*): 70% after 20 days, no lag phase; plateau phase after 20 days	[90]
Bioplastics (PCL) in powder form (SigmaAldrich, M_n *43700*) PLA (Unitika) (M_n *100500 g/mol*)); Cellulose microcrystalline: reference material	Anaerobic sludge (biomass Plant cow manure & vegetable waste); *55 °C*, stirred*: 1 min/d;* Anaerobic biodegradation tests on solution portion of 4 different stage sludges (7d, 12d, 18d, 40d); At 7d after preincubation start: *TS: 2.0%, VS 1.0%, C/N 1.4, pH 8.0, TOC: 0.27%*	Degree of biodegradation (end of test): cellulose: 91%-95%; PLA: 86%-95%; Pre-incubated sludge at 18d: highest biodegradation activity of PLA	[137]
Cellulose microcrystalline (reference). PLA (H-400) [138].	Anaerobic sludge from Biomass Plant (cow manure and vegetable waste); aquatic conditions; thermophilic (*55 °C*): (*TS: 2.1%, VS: 1.0%, TOC: 0.4, C/N: 2, pH: 8.5*); mesophilic (*35 °C*): (*TS: 2.2%, VS: 1.1%, TOC: 0.4, C/N: 2, pH: 8.3*)	Degree of biodegradation (*35 °C*)*:* cellulose: 80% (15d). PLA: started at 55 days; biodegradation rate: 2.9%/week, discontinued test. Degree of biodegradation (*55 °C*)*:* (cellulose: 80% (13d). PLA: 60% (30d), 80% (40d), 90% (60d); End of test including CO_2 dissolved in sludge: cellulose 87% (35 °C), 93% (55 °C); PLA: 94%, 92% (55 °C)	[139]
PHAs			
PHA (PHA-4100, Metabolix), (PLA NatureWorks™) Cellulose:(Avicel PH-101): positive control LDPE: negative control	Lab testing (ASTM 5511): 37°C, 4-8g of plastic /l inoculum (pH = 7.8; FOS = 1.08g/l; TAC = 6.49g/l	Biodegradation: PHA:100% (14d); PLA: <10 % (20 d); Cellulose: 40% (4-20d); Polyethylene: 0% (20d)	[98]
PHB	Conditions: excess activated sludge with and without PHB accumulation: (ES_{PHB}) and (ES), mixed with digested sludge (DS), anaerobic	Degree of PHB biodegradation: ES_{PHB}+DS:>75% (2d), 90% (34d); ES+DS: 56% (2d), 56% (34d)	[140]

	fermentation at *37°C*, stirring, sludge retention time: 23d; *VS (mg/l): DS: 9750, ES: 13600,* ES_{PHB}*: 19200;* *Start up: ES+DS: pH 8.1,* ES_{PHB}*+ DS: pH 8.7*	Within 34 d: CH_4 gas from ES_{PHB} 25 % > than ES	
Various bio-based plastics and blends			
Cellulose-based films (metallised, heat-sealable and non-sealable, high barrier), Cellulose diacetate film: CDF), starch-based films blends, PLA film, PLA blend pellets (PLAB)	Anaerobic digesters - conditions: 37 °C; semi-continuous operation. Operation after pre-acclimatisation: organic loading rate (OLR): 2 kg VS m^{-3} d^{-1} (147d); feedstock (VS basis): 80% food waste, 18% card packaging, 2% bioplastic; solids retention time (SRT): 50d; removal 560 g digestate/ week; bioplastic feeding: 0d, PLAB addition: (7d)	Calculated solids destruction: cellulose (65d): 89%-98%, Cellulose diacetate: 10%, starch based: 11%, 18%, PLA film: 20%, PLA blend: 3%, food waste: 84%, card packaging: 70%; PLAB and CDF: not degraded; PLAF some biodegradation over a longer period; bioplastics: no inhibition or destabilisation of digestion process (177d)	[141]
Bioplastics in powder form (SigmaAldrich): PBS (M_n *50000 g/mol*)), PHB (M_n *152000 g/mol*)), PCL (M_n *44000 g/mol*)), PLA (Unitika) (M_n *80000 g/mol*)); Cellulose microcrystalline: reference material (Merck)	Anaerobic sludge from Biomass Plant (operated with cow manure and vegetable waste); Anaerobic biodegradation tests: on solution portion of sludge pre-incubated for 16d: *55 °C,* stirred*: 1 min/d; TS: 0.86%, VS 0.57%, C/N 0.8, pH 8.4, TOC: 0.09%.*	Degree of biodegradation: cellulose: >90% (10d), PHB: >70% (11d), PCL: 40% (30d), 80% (60d), PLA: 24% (30d), 68% (60d), anaerobic biodegradation rates: PHB > PCL > PLA, PBS: no biodegradation	[142]
Bioplastics in powder form (SigmaAldrich): PBS (M_n *50000 g/mol*)), PHB (M_n *152000 g/mol*) *0),* PCL (M_n *44000 g/mol*)), PLA (Unitika) (M_n *80000 g/mol*)); Cellulose microcrystalline: reference material (Merck)	Anaerobic sludge from Biomass Plant (operated with cow manure and vegetable waste); *37 °C, pH 8.0*	Degree of biodegradation (37 °C, 2 runs): PLA: 7% (90 d), 18%, 27% (182d), 26%, 43% (277d); PHB: 35%, 42% (4d), > 90% (10d) (sludge with lower activity able to rapidly biodegrade PHB); PCL: 0%, 6% (118d), 1%, 11% (182d), 3%, 18% (277d); PBS was not biodegraded Low anaerobic biodegradation rates of PLA and PCL treatment of PBS, PCL and PLA at *37 °C* in anaerobic commercial fermentation tanks: unsuitable Anaerobic biodegradation rates at *37°C* and *55 °C (other sources, e.g. [143])*: PHB: the same, PLA, PCL: higher at *55* °C: PLA: (75% (40-75d), PCL: 80 % (30-50 d)	[144]

		PBS: no biodegradation in both cases	
Ecobras^{TM} [145] (Co-polyester + corn-based plastic, plastarch, cellulose paper: reference material (positive control) PP + 2% additive, PETE+ 1% additive	High-solids AD conditions (ASTM D5511); active methanogenic inoculum from an AD treating municipal sewage sludge; mesophilic range *(37°C)*, TS: 9%, VS: 59.5%, TOC 37%, pH: 8.3	Degree of biodegradation: cellulose paper: 74±5%; Plastarch: similar to cellulose (7d), slowed through 28d, final (50 d): 26±4%; corn-based plastic (50 d): 20±4%; Mean methane content: 54±6%. Plastics containing additive: no mineralization	[146]
Mater-Bi (MB) [114], Cellulose filter paper (CFP): positive control.	ASTM D5526; anaerobic sludge; stirred manually; VS 67%	Cumulative methane gas production at 17d: MB:160.5 ml CFP: 220.8 ml; at the end of test (32d): MB:245 ml, CFP: 246.8 ml; decrease of VS (32d): MB: -34.7%, CFP: -35%	[116]
PHB, PHBV, PCL, synthetic polyesters: poly(trimethylene adipate): (PTAd), poly(tetramethylene adipate): (PTMA), Aliphatic-aromatic copolyesters from 1,4-butanediol (BDO), terephthalic acid (TA), and adipic acid (BTA-copolymers) or (PBAT-copolyesters)	Microbial consortia (3 sludges, 1 sediment), isolated strains (*Clostridium or Propionispora*)	Degree of biodegradation: PHB>PHBV>>PCL; PHB faster than PHBV in contrast to aerobic conditions; PTAd, PTMA, BTA-copolymers: very low anaerobic microbial susceptibility; High TA copolyester (BTA 40:60) under thermophilic conditions, blended with starch: no anaerobic breakdown; Selected anaerobic strains able to depolymerize polymers by means of different degrading enzymes	[147]
PCL (TONE^{TM} polymer P-787) [148], PLA [104], Mater-Bi (MB)： blend starch+polycaprolactone [114], PBAT (Eastar bio (EB))[149], cellulose：positive degradation reference	Anaerobic conditions during a period of 28 days (ISO 14853); microbial inoculum from wastewater treatment plant digester. Predigestion of OC in sludge at *35°C;* incubation: *35°C,* regularly stirred.	Degree of biodegradation: cellulose: 62.2%, MB: 23%; PCL, PLA, PBAT: no biodegradation; Biogas produced: cellulose: 570 ml/g, MB: 220 ml/g	[150]
PHB (Biopol BX G08), (M_w= *540000 g/mol*) PHBV (11.6%-β-hydroxyvalerate, Biopol BX P027) (M_w= *397000 g/mol*) [151], PCL (M_w= *50000 g/mol*), PCL Tone 787 (M_w= *200000 g/mol*), PCL-S (caprolactone-starch); (M_w= *187000 g/mol*), SP (1,3-propanediol/adipic acid, 1,4-butanediol/adipic acid),	Inoculum: -Methane sludge (anaerobic laboratory reactor fed with waste water from sugar industry) (LS, 37°C); -Sewage sludge (anaerobic digester of municipal waste water treatment plant) (WWS, 37°C); -thermally treated biowaste (TBW, , 50°C) from anaerobic biowaste treatment plant,	Degree of biodegradation (biogas formation) /disintegration (mass loss) (42d, 37°C): PHB: 100%/100% (LS), 100%/100% (WWS); PHBV: 29%/57% (LS), 31%/63% (WWS); PCL:16%/30% (LS), 17%/30% (WWS); SP :1.1%/1.2% (LS), 11%/2.1% (WWS); BTA: 5.5%/0.5% (LS), 11%/1% (WWS); Degree of disintegration (TBW: (thermophilic conditions 50 °C): PHB, PHBV: 100%, (21d),	[152]

BTA (1,4-butanediol -adipic - terephthalic acid)	--sample from anaerobic river sediment (AS); mixed cultures, isolated strains; 37°C	PCL: 54% (42d): 28fold increase under thermophilic conditions as compared to mesophilic conditions PHB > PHBV: 3-hydroxyvaleric acid may inhibit anaerobic microorganisms	
PHA-4100 [153], PLA [104], sugar-cane, Cellulose Avicel PH-101, (positive control)	AD high-solids conditions (ASTM 5511): Inoculum (pH = 7.76; FOS = 1.08g/L; TAC = 6.49g/L, 37°C (from a 2 stages mesophilic semi-continuous AD plant).	Degree of biodegradation (mesophilic): PHA >90% (11-12d), 95-100% (15d) >> microcellulose (PHA biodegraded significantly more than the microcellulose positive control); gas composition CH_4 ~ 60%; biodegradation: PHA, cellulose, sugar cane: yes, PLA: no	[154]

Feasibility TESA criterion indicators: A brief overview of proposed indicators for the “feasibility” TESA criterion of organic recycling of post-consumer/industrial bio-based plastics is shown in Table 3 and Table 4.

Table 3. Proposed indicators for the industrial aerobic composting feasibility TESA criterion

Indicators	Metrics
Industrial aerobic composting feasibility TESA Criterion	
Biodegradability	• *Biodegradable under industrial aerobic composting conditions* ***(Yes/No)***
Sorting efficiency	• η_{sort} *(%) = mass of sorted biodegradable, under aerobic industrial conditions, post-consumer bio-based plastics (kg) x100/ mass of the collected non-recyclable post-consumer bio-based plastics or separate collected post-consumer biodegradable bio-based plastic streams (kg)*
Compostability	• *Compliance with standard specifications for compostability under industrial aerobic composting conditions* ***(Yes/No)***

Table 4. Proposed indicators for the anaerobic digestion feasibility TESA criterion

Indicators	Metrics
Anaerobic digestion feasibility TESA Criterion	
Biodegradability	• *Biodegradable under anaerobic digestion conditions* ***(Yes/No)***
Sorting efficiency	• η_{sort} *(%) = mass of sorted biodegradable, under AD conditions, post-consumer bio-based plastics (kg) x100/ mass of the collected non-recyclable post-consumer bio-based plastics or separate collected post-consumer biodegradable bio-based plastic streams (kg)*
Anaerobic digestibility	• *Compliance with standard specifications for biodegradability under AD conditions* ***(N/A)***

3.4 Economic viability criterion

Infrastructures for organic recycling**:** A basic prerequisite, for considering organic recycling, industrial composting and/or AD, as suitable EoL options for bio-based products, is the infrastructures availability. The availability of industrial composting facilities and AD facilities that accept bio-based plastics in the region and/or the distance of available infrastructures, turn these options, into attractive alternative EoL routes, or not.

In general, the operation of industrial composting facilities requires planning consent and environmental protection licensing that needs to be considered in the definition of the availability of suitable facilities indicator [3]. AD sites, as waste management facilities, have to be run with a license too. Substantially, the license has conditions to ensure that the authorized activities will not cause negative effects on the environment, on human health or on the local communities. Several potential problems, that have to be regulated, such as safety considerations, problems associated with the environment such as odours, emissions, noise, disposal of effluents from the processes etc., can be included on the working plan produced and required for the corresponding licenses [57].

Proposed indicator: Availability of licensed aerobic composting and/or AD facilities for organic recycling of non-recyclable post-consumer /industrial biodegradable products. Indicative qualitative metrics:

- *Availability of licenced industrial aerobic composting and/or AD facilities in the region*

Availability of bio-based plastic waste for organic recycling: A guaranteed long-term supply of (municipal, green) bio-waste feedstock is necessary before the establishment of an aerobic composting or AD plant that also accepts certified, under the corresponding conditions, post-consumer bio-based biodegradable plastics, at a maximum allowed percentage of the bio-waste feedstock. Especially for closed/contained composting systems, it is important that they operate near or at their maximum design capacity, so as to be economically viable. Likewise, the organic feedstock inputs to AD facilities are required to be guaranteed.

An estimated annual quantity of 30 Mt of bio-waste, separately collected, is composted or digested in approximately 3500 industrial aerobic composting or AD facilities across Europe, according to survey data provided by the European Compost Network (ECN) [10]. The bio-based plastics production capacity is set to increase from around 2.11 Mt in 2019 to approximately 2.43 Mt in 2024 and the biodegradable bio-based plastics from 1.17 Mt in 2019 to reach approximately 1.33 Mt in 2024 [14]. Based on current statistics, the availability of sufficient supply of bio-waste feedstock is not expected to be influenced by the quantities of the available and acceptable compostable bio-based plastic waste routed to industrial composting. The effect of the compostable bio-based plastic on the industrial aerobic composting facility operation may be controlled by setting a maximum allowed percentage of certified bio-based biodegradable plastics to the total bio-waste feedstock.

The quantities of collected and sorted post-consumer compostable bio-based plastics, available per year, are described through a proposed quantitative indicator:

- *Material availability (%) = Supply of collected and sorted post-consumer /industrial compostable bio-based plastic (kt) available per year (an) x100 / capacity of the industrial aerobic composting facility in the region to process a maximum allowed quantity of compostable bio-based plastic (kt/an)*

Anaerobic digestion requires a minimum amount of bio-waste material for the process to be technically feasible (to stabilize temperature, moisture). Depending on local conditions and the type (origin) of bio-waste, this minimum amount ranges from 1 to 5 kt/an. If co-digestion (with agricultural wastes or sewage sludge) is applied, there is no lower weight limit [155]. Similarly, to aerobic composting, the quantities of collected and sorted post-consumer digestible bio-based plastic, available per year, are described through a proposed quantitative indicator:

- *Material availability (%)* = *Supply of collected and sorted post-consumer /industrial digestible bio-based plastic (kt) available per year (an) x100 / capacity of the AD plant in the region to process a maximum allowed quantity of digestible bio-based plastic (kt/an)*

Organic recycling products quality*:* As already mentioned, the contribution of the post-consumer /industrial bio-based plastics to the final products of organic recycling of bio-waste is expected to be rather insignificant. It may however influence the quality of the produced compost, digestate and/or biogas. The quality of the final products of organic recycling (namely compost, digestate and biogas respectively), has strong impact on the economic viability of the corresponding facilities. For example, the fertilising products Regulation [11] armonised the quality standards for the compost and AD products in the EU internal fertilisers market, promoting the competitiveness of the recycled organic fertilisers and soil improvers [156, 157]. In the case of AD, the production and quality of biogas generated, should meet the relevant specifications (e.g. ISO 20675:2018) [87].

Compost quality*:* The compost quality is mainly affected by the municipal bio-waste and green bio-waste used as feedstock and also the infrastructures and operating conditions. Concerning the acceptance of post-consumer compostable plastics, the corresponding specifications should be met, along with the necessary quality screening at the entrance of the facility. The separate collection and quality of the post-consumer compostable bio-based plastics affects also the price for their acceptance to the composting facility. The specifications for separate collection of compostable feedstock (municipal bio-waste, green bio-waste) should also be met by the post-consumer compostable bio-based plastics to allow for cost efficient composting processing. The separate collection of bio-waste for aerobic composting is already a requirement set by the Directive (EU) 2019/1009 [11].

The quality of the separate collected and sorted post-consumer compostable bio-based plastics, including the additives present in the plastics, should not affect the quality of the end product (commercial compost) and its certification and use as organic fertilizer or soil improvement compound. The resulting compost must be free of contamination, residues, pathogens and heavy metals so to meet the requirements and to be appropriate for valorization through the market of fertilisers and soil improvement compounds. Contamination (non-compostable parts) and parameters affecting negatively the soil productivity influence the final market price and the economic viability. The possibility and the ability of providing to the market a compost product that meets the requirements of the Directive (EU) 2019/1009 [11], by using the available feedstock and the appropriate composting technology, is a critical issue also for the acceptable certified compostable bio-based plastics.

Proposed *qualitative indicator* for the quality of the compost: Compost quality from aerobic composting and AD of biowaste including non-recyclable post-consumer / industrial biodegradable bio-based plastics should not be inferior to compost quality from aerobic composting and AD of pure biowaste. Indicative qualitative metrics:

- *Compost quality from industrial aerobic composting and AD of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, meets the relevant specifications for quality of the fertilising products Regulation in the same way as the compost produced from pure biowaste*

Biogas quality: In order to be used as an upgraded biomethane energy source, biogas would require treatment for its refinement. The main limitation set by the environmental legislation concerns the hydrogen sulfide (H_2S) levels present in biogas. H_2S, may be produced during the last stage of AD, during methanogenesis [61]. This highly toxic and flamentable product is among the main chemical components to be removed from biogas (Occupational Safety and Health Administration (OSHA) ceiling: 20 ppm) [158]. In addition to toxicity, the H_2S is highly corrosive (e.g. hydrogen sulfide corrosion (HSC) of steels) and so, when biogas is to be used as fuel it should meet the quality requirements for the utilization equipment. To face this problem, the main treatments applied, include gas scrubbing and cleaning (typically by amine gas treatment technologies) [159]. If the gas impurities are left untreated, they can increase the maintenance requirements of the equipment fuelled by the gas and thus reducing equipment duration. In addition, the effective gas utilization requires gas cleaning to reduce condensation and ensure the removal of siloxanes (suspicious of chronic toxicity due to bioaccumulation) [160,161]. Thus, gas cleaning is a prerequisite for several serious reasons. Biogas cleaning is a capital-intensive, multistage operation that can also carry high maintenance costs due to media replacements and/or power costs. On the other hand, biomethane is an added value renewable energy/fuel product equivalent to fossil-based natural gas. Post-consumer /industrial biodegradable bio-based plastics accepted in AD facilities should meet specifications that ensure no contribution to the biogas quality degradation. Indicative qualitative metrics:

- *Biogas quality produced from AD of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, meets the relevant specifications for quality of biogas in the same way as the biogas produced from AD of pure biowaste*

Market of post-consumer/ industrial biodegradable plastics for organic recycling: Ensuring successful industrial composting and/or AD plant development and operation with strong impact on the economic viability of the organic recycling of non-recyclable bio-based plastics along with biowaste, requires availability of markets for the end-products (compost and biogas).

Compost: The market price for a specific quality of compost in the form of certified organic fertilisers and/or soil improvement compounds is a crucial factor of the economic viability criteria. The determination of available markets for the end-products constitutes a factor that can ensure a successful industrial composting plant development and function. The ability to obtain a product that can be sold creating an additional income, provided that the main operation cost is covered by the municipalities, is critical for the economic viability especially of the industrial aerobic composting EoL option. The Regulations set by the EU] [11] and the US [47, 48], as already mentioned, is expected to facilitate the market accessibility of these products.

Concerning AD, a critical issue for the digestates market (and for organic fertilisers market in general) is their concentration in heavy metals. The market value of these products, mainly as soil conditioners, or fertilizers, depends on the compliance with the governing quality standards with respect to the heavy metals' concentration, but also on the guarantee of a pathogen and seed free product [162]. All these requirements are covered now by the compliance with the fertilising products Regulation [11]. Concerning MSW, their organic fraction when is mechanically separated is more difficult to meet these strict requirements. This is expected to be overcome with the implementation of the requirement for source separated fractions which meet the quality standards more easily [163].

Biogas: There is a trend in several Member States to shift from composting to AD or to combined AD and composting treatment of the digestate because the municipalities are able to negotiate lower gate fees to biowaste operators thanks to increased competition in the biowaste treatment sector and the lower price for digestate. As a result, biowaste operators are forced to generate revenue through other options, such as the sale of electricity from biogas production [164].

The market of post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, is strongly influenced by the market of the end-products of organic recycling (compost, biogas), even though the biodegradable bio-based plastics do not contribute significantly to the final compost products of the industrial aerobic composting facilities or to digestate of the AD facilities.

Proposed indicator: Market of non-recyclable post-consumer /industrial biodegradable bio-based products for organic recycling. Indicative metrics:

- *Gate fee for non-recyclable post-consumer bio-based biodegradable plastics to be accepted at a max percentage of the feedstock supply for organic recycling by facilities of industrial aerobic composting or AD*

Estimated financial feasibility: The financial feasibility of the EoL options is based on the economic data and can be described in terms of the profitability of the processes. The existence of relevant data is very limited for bio-based post-consumer / industrial plastics. For organic recycling the financial data available for composting and AD of biowaste may also be considered applicable for compostable bio-based plastics treated together with biowaste, except for the gate fee.

CAPEX and OPEX costs and revenues should be estimated for each facility as crucial parameters that determine the net profit and so the financial feasibility of the enterprise [165].

Proposed indicators to describe the profitability of the processes: Estimated financial feasibility of organic recycling of bio-waste together with non-recyclable post-consumer /industrial bio-based biodegradable plastics at a max allowed percentage of biowaste. Indicative metrics:

- *Return On Investment for organic recycling (ROI)*
- *Net Present Value for organic recycling (NPV)*

The return on investment (ROI) is measured as a ratio or percent (net investment/ initial investment) and the Net Present Value (NPV) is the present value of benefits minus costs [166].

Economic viability TESA criterion indicators*:* A brief overview of proposed indicators for the "Economic Viability" TESA criterion of organic recycling of post-consumer/industrial bio-based plastics is shown in Table 5.

Table 5. Proposed indicators for the economic viability TESA criterion

Indicators	Metrics
Economic Viability TESA Criterion	
Infrastructures for organic recycling	• *Availability of licenced industrial aerobic composting and/or AD facilities in the region* ***(Yes/No)***
Availability of bio-based plastic waste for organic recycling	• ***Material availability (%)*** *= Supply of collected and sorted post-consumer /industrial compostable bio-based plastic (kt) available per year (an) x100 / capacity of the industrial aerobic composting facility in the region to process a maximum allowed quantity of compostable bio-based plastic (kt/an)* • ***Material availability (%)*** *= Supply of collected and sorted post-consumer /industrial digestible bio-based plastic (kt) available per year (an) x100 / capacity of the AD plant in the region to process a maximum allowed quantity*

	of digestible bio-based plastic (kt/an)
Organic recycling products quality	• *Compost quality from industrial aerobic composting and AD of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, meets the relevant specifications for quality of the fertilising products Regulation in the same way as the compost produced from pure biowaste **(Yes/No)*** • *Biogas quality produced from AD of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, meets the relevant specifications for quality of biogas in the same way as the biogas produced from AD of pure biowaste **(Yes/No)***
Market of biodegradable products for organic recycling	• *Gate fee for non-recyclable post-consumer bio-based biodegradable plastics to be accepted at a max percentage of the feedstock supply for organic recycling by facilities of industrial aerobic composting or AD*
Estimated financial feasibility	• *Return On Investment for organic recycling **(ROI)*** • *Net Present Value for organic recycling **(NPV)***

3.5 Common environmental and techno-economic criterion

Organic recycling efficiency*:* The percentage of the post-consumer /industrial bio-based biodegradable plastics converted into biomass is very small due to the high biodegradation rates to be achieved by these materials in order to be certified as biodegradable under aerobic composting or AD conditions. The biodegradation efficiency is measured by the bio-based carbon content of the product closing of the carbon loop, in the form of the evolved CO_2. In addition, the biogas obtained describes the efficiency of renewable energy recovery in the form of CH_4 from part of the bio-based carbon content of the sorted post-consumer biodegradable plastic mass entering the AD facilities together with biowaste. *Proposed metrics:* Organic recycling efficiency from post-consumer biodegradable bio-based plastic mass under aerobic composting and AD conditions.

- *Biogas mass recovery efficiency from AD of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, as compared to biogas mass recovery efficiency from AD of pure biowaste*
- *Closing the biogenic carbon loop efficiency through the biodegradation of post-consumer bio-based plastic mass under aerobic composting conditions*

- *Note 1: Measured by the degree of biodegradation of biodegradable bio-based plastic (e.g. 95%): bio-based organic carbon released in the form of* CO_2 *contributes to closing the biogenic carbon loop; the remaining biomass and non-biodegradable (non-toxic) additives are incorporated with the compost to the soil*
- *Note 2: The fossil-based part of the biodegradable post-consumer biodegradable bio-based plastic mass (if any), converted into* CO_2 *or gas under aerobic composting and AD conditions, is lost for the fossil deposits and it is considered pollutant, entering the biological carbon cycle*

Two additional quantitative metrics for the aerobic composting and the AD respectively can be described as follows:

- $\eta_{mr}(\%)$ *= mass of sorted post-consumer compostable bio-based plastic actually composted (kg) x 100 / mass of the sorted post-consumer compostable bio-based plastic used as feedstock (kg)*
- $\eta_{mr}(\%)$ *= mass of sorted post-consumer biodegradable, under AD conditions, bio-based plastic actually converted into biogas (kg) x 100 / mass of the sorted post-consumer, biodegradable under AD conditions, bio-based plastic used as feedstock (kg)*

The additives impact on sustainability of organic recycling: The efficiency and nature of the additives used in both the aerobic composting process and the AD of biowaste, including the additives used specifically with compostable bio-based plastics, may affect the techno-economic and environmental sustainability of the process [167,168].

Proposed metrics: Impact of the additives used with aerobic composting and AD of non-recyclable post-consumer /industrial biodegradable bio-based products on sustainability is included in the indicators of the quality of the produced compost and biogas.

- *Nature and impact of additives used with bio-based plastics under aerobic industrial composting and AD conditions*

More specifically, the composting efficiency is influenced by the nature of the biowaste and possibly of the bio-based plastics present. It may also be affected by the nature of the additives used with the bio-based compostable plastics (depending on application and processing requirements; e.g. stabilisers, compatibilisers etc.). Emphasis should be placed on the use of environmentally benign bio-based and natural additives with the bio-based plastics, that are also compostable or not interfering with the composting process and the soil ecosystems. For example, tannin esters, investigated as potential UV stabilizers for biodegradable polymers [169], are also known to function as antimicrobial agents and enzyme inhibitors. The evaluation of the compliance of a bio-based compostable plastic with the requirements of EN13432 or equivalent standards should reveal any negative effects of the additives used with a specific product. The compliance of the compost produced with the specifications of the fertilising products Regulation [11] should also ensure its safety or reveal possible problems due to additives used with the compostable plastics.

Additives may also be used to enhance the composting process efficiency of organic wastes and the quality of the final product but also to enhance the compostability of bio-based plastics. For this purpose, various types of additives are available commercially, including mixtures of different amounts /types of microorganisms and/or additives such as mineral nutrients, or various forms of readily available carbon [167]. Various additives such as fly ash, phosphogypsum, jaggery, lime, and polyethylene glycol used in the green waste composting were shown to affect in different ways the microbial growth and the enzymatic activities, the organic matter biodegradation and the quality characteristics and bulk density of the final compost product. The best effect in the composting efficiency of green waste and the quality of the compost were obtained by jaggery and polyethylene glycol [167].

Among the commercial additives included are pH-controlling compounds (e.g. alkaline minerals, ash and lime) aimed at increasing the compost pH levels [167]. The use of lime ($CaCO_3$) as additive to control acidity should be avoided not only because it increases the cost (material and labour) but also because it results in the loss of ammonium nitrogen (NH_4-N) to the atmosphere in the form of ammonia gas (NH_3) that causes odours and depletion of valuable nitrogen, degrading in this way the quality of the final compost product. Instead, the proper way to handle prolonged acidity is a good control of aeration, temperature and mixing.

Concerning compostable bio-based plastics, it has been reported that PLA biodegrades at slower rates as compared to organic waste and in some cases, it may not fully break down by the time organic waste (e.g. food) and green bio-waste are composted. This may result in PLA remains accumulation in the compost and difficulties in distinguishing contamination problems due to conventional plastics from incomplete biodegradation of PLA [84]. Research has been carried out to investigate the possible use of industrial alkaline wastes as a potential resource for compost alkaline additives to enhance the biodegradation rate of PLA under industrial composting condition to the same composting rate as biowaste and green waste. This would allow for the compost screening process optimization and cost efficiency, applied to remove only non-degradable plastic residues, reducing in this way the amount of waste rejected to landfill and enhancing the quality of the final product. Among the industrial alkaline wastes investigated are residues already tested as soil improvements to increase soil pH, including a byproduct of aluminium manufacturing, bauxite residue, wood fly ash containing K_2CO_3, and MgO. Another possible alkaline additive investigated in [84] is a steel production slag byproduct (mineral CSA) that contains Ca_2SiO_4. The results obtained suggest that the addition of alkaline amendment to the industrial composting flow together with compostable bio-based plastics could enhance their composting rate enabling their acceptance by the industrial composting facilities [84]. Another technique proposed for commercial application is the addition of selected specific microbial strains (bioaugmentation) capable to accelerate the biodegradation of compostable bio-based plastics under aerobic composting conditions. It has been shown that bioaugmentation allowed bio-based plastics such as PLA and PLA bio-nanocompostites, to biodegradade at comparable time frames to those of organic materials [127].

Proposed metrics: The nature of the used additives in the aerobic composting process, to enhance composting efficiency of compostable bio-based plastics, with emphasis placed on the use of environmentally benign additives that are natural substances or compostable bio-based compounds.

- *η_{add} (%) = mass of environmentally benign natural or bio-based compostable additives (kg) x 100 / mass of total additives used with the bio-based plastics during the aerobic composting process (kg)*

Regarding processes and additives in general, both, AD and aerobic composting, are based on natural biological processes with a minimum input of additives [170]. In AD, processing chemicals are sometimes added to improve the performance of the involved microbes in biodegrading biowaste, including bio-based plastics, avoid foaming, and to bind S which – as H_2S – is damaging for biogas incineration equipment. A range of chemicals may be relevant. The implications for the use of the produced digestates in certified organic agriculture remain to be clarified [171].

Proposed metrics: Analogous to composting, a quantitative indicator is proposed, of the environmentally benign bio-based, biodegradable under AD conditions additives, used in the AD process as compared to total amount of the additives used with the bio-based plastics entering the process.

- *η_{add} (%) = mass of environmentally benign natural or bio-based biodegradable under AD conditions additives (kg) x 100 / mass of total additives used with the bio-based plastics during the anaerobic digestion process (kg)*

***Resources utilisation efficiency**:* The overall environmental and techno-economic sustainability of organic recycling processes of biowaste that includes also post-consumer bio-based plastics, is affected significantly by the efficiency of the utilities used for the processes and their renewability and/or recirculation. The energy used may be derived from renewable and/or conventional sources while the water used may partially come from a closed recycling loop of the wastewater or rain water [172].

Proposed metrics: Utilisation efficiency of resources used for organic recycling of biowaste that includes post-consumer/industrial bio-based products, accepted at a max percentage of the feedstock supply, as compared to organic recycling of pure biowaste:

- *Total water consumption efficiency*
- *Wastewater and rain water recirculation*
- *Total energy consumption efficiency*

- *Renewable energy use / total energy consumption*

In the case of aerobic composting, depending on the technology available (windrow composting, aerated static piles, in vessel composting) the inputs and the outputs of the process (mass and energies balances) differ and so does the environmental and techno-economic sustainability outcome. The choice of the technology to be applied must be connected to its versatility to handle possible changes in feedstock type, quantity and seasonality, as well as the compostable plastics processed [173]. The characteristics of the inputs and the outputs contribute to the overall techno-economic and environmental sustainability analysis of the process. Apart of the quantity and optimization of the characteristics of the feedstock for high mass recovery efficiency, the minimization of utilities used for the process (for example energy, water and air) is very important. The same apply in the AD case.

The proposed metrics in the form of quantitative measures for the water consumption and the water conservation through recycling within the process can be described as follows (the generation of solid waste through wastewater treatment and its possible valorisation is not considered):

Total water consumption efficiency: In the case of organic recycling, this stands for the total water quantity used in the aerobic composting or AD processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced with respect to the total water quantity used in the aerobic composting or AD processing of bio-waste per unit mass of compost or biogas produced

- η_{water} *(kg/kg) = Total water consumption for the aerobic composting or AD process of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply (kg/kg compost or kg/kg biogas) / Total water consumption for the aerobic composting or AD process of biowaste (kg/kg compost or kg/kg biogas)*

Wastewater and rainwater recirculation: The quantity of water recovered through water recycling for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics to the total quantity of water used in the aerobic composting process or in the AD process:

- η_{Rwater} *(%) = quantity of water recycled in the organic recycling process for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics (kg) x 100 / quantity of total water usage (kg)*

The proposed metrics in the form of quantitative measures for the energy consumption and the energy conservation through the partial use of renewable energy within the process can be described as follows.

Total energy consumption efficiency: Total energy consumption including fossil-derived plus renewable - internally derived energy that is required for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced with respect to the energy consumption required in the aerobic composting or AD processing of bio-waste per unit mass of compost or biogas produced (kWh/kg). This ratio is a useful metric capturing the efficiency of consumption of energy when processing biodegradable plastics together with bio-waste as related to the mass of the compost and/or biogas produced from the process of biowaste:

- η_{energy} *(kWh/ kWh) = Total energy consumption required for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics per unit mass of compost or biogas produced (kWh/kg)/ Total energy consumption (kWh) required for the aerobic composting or AD of bio-waste per unit mass of compost or biogas produced (kWh/kg)*

Renewable energy use / total energy consumption: The energy derived from renewable sources to the total energy consumption for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics. This ratio provides evidence on renewable energy (internally produced or externally provided) usage as related to the total energy consumption:

- $\eta_{Renergy}$ *(%) = kWh of energy derived from renewable sources for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics x 100 / total kWh of energy consumption*

Waste – Emissions impact on sustainability of organic recycling: Waste streams generated from aerobic composting, such as leachate, residuals, odours, air emissions and in AD anaerobic digestion effluents (ADEs) may have an important techno-economic impact in addition to the obvious environmental impact, since they can prohibit the operation by excessive cost or inability to capture or dispose unwanted waste / effluents.

More specifically, considering aerobic composting, concerning the outputs, apart from the main product, compost, minimizing emissions, odours, leachate generated from the composting process are important techno-economic and environmental sustainability issues. Most of the technologies claim to have solved these problems but, in some cases, this is not feasible and relative problems occur i.e., with odours which consists a problem requiring high-cost interventions to control, or frequently is impossible to rectify. This affects also the social sustainability of the composting option, directly related with the siting of the facility. Solid waste includes rejected foreign or non-compostable articles which are routed to incineration or landfilling. Non composted bio-based plastics can be recirculated back to the feedstock pre-treatment phase.

Respectively, waste streams generated from AD process (e.g., AD effluents) may have important techno-economic and environmental sustainability impact. There are potentially gas emissions (e.g., H_2S) from AD, which should be minimized as much as possible. However modern plants are assumed to be well-designed and managed. If the question concerns a new plant, decision makers should consider a well-designed and managed plant with very small (negligible) atmospheric emissions [155].

Besides renewable energy, biogas plants also produce large amount of liquid anaerobic digestion effluents (ADEs) which may lead to oversupply of ADEs in a short time. ADEs still have high chemical oxygen demand (COD) and they are rich in nitrogen and phosphorus, which excludes the possibility of these wastewaters discharge directly to the environment. Thus, a low-cost method to treat ADEs is needed [174]. Considering both the characteristics of ADEs and nutritional needs of algae, it seems that ADEs may be a useful source of nutrients and microelements to ensure an intensive growth of microalgae biomass with simultaneous contaminants biodegradation [175,176,177].

Accumulation of potentially toxic elements (PTEs) is a common concern related to composts and digestates from urban organic wastes (UOWs). PTEs can accumulate in soils after long term application of treated urban wastes. Some urban organic wastes' composts and digestates may fail the current thresholds for potentially toxic elements. These elements, e. g. zinc, may not only originate from the organic waste, but also from mechanical treatments [171]. Digestates may have higher concentrations of potentially toxic elements on a dry matter base comparing to composts. However, the soil accumulation risk is likely much lower than for composts [171].

Fertilizers from organic waste may contain significant amounts of persistent organic pollutants (POP) such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) [171]. It is therefore important to apply the strict specifications set by the fertilising products Regulation [11].

In the case of the aerobic composting or AD of bio-waste together with a maximum allowed percentage of non-recyclable post-consumer /industrial bio-based biodegradable plastics routed to organic recycling, the key question concerns possible effects on the waste and emissions produced as compared to processing of bio-waste alone, that could impact the sustainability of organic recycling. The compliance of the compostable bio-based plastics to the thresholds set by the corresponding standard specifications (e.g. for heavy metals) alleviates such risks.

Proposed metrics for possible effects of compostable bio-based plastics: Impact of the waste – emissions associated with the aerobic composting and AD of a maximum percentage of non-recyclable post-consumer /industrial biodegradable bio-based products in the biowaste to be treated on:

- *Specific gas emissions*
- *Residuals, solid waste*

- *Leachate or AD effluents*

More analytically the metrics for both aerobic composting and AD processes can be described as:

- *Specific gas emissions (kg/kg) = quantity of specific gases emitted during the organic processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced from the process (kg/kg)*
- *Solid waste (kg/kg) = quantity of solid waste rejected from the organic processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced from the process (kg/kg)*
- *Leachate (kg/kg) = quantity of leachate or effluent generated from the organic processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced from the process (kg/kg)*

Common environmental and techno-economic criterion indicators*:* A brief overview of proposed indicators for the "Common environmental and techno-economic criterion" TESA criterion of organic recycling of post-consumer/industrial bio-based plastics is shown in Table 6 **.**

Table 6 . Proposed indicators for the Common environmental and techno-economic criterion TESA criterion

Indicators	**Metrics**
Common environmental and techno-economic TESA Criterion	
Organic recycling efficiency	• *Biogas mass recovery efficiency from AD of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply, as compared to biogas mass recovery efficiency from AD of pure biowaste* • *Closing the biogenic carbon loop efficiency through the biodegradation of post-consumer bio-based plastic mass under aerobic composting conditions* • η_{mr}*(%) = mass of sorted post-consumer compostable bio-based plastic actually composted (kg) x 100 / mass of the sorted post-consumer compostable bio-based plastic used as feedstock (kg)* • η_{mr}*(%) = mass of sorted post-consumer biodegradable, under AD conditions, bio-based plastic actually converted into biogas (kg) x 100 / mass of the sorted post-consumer, biodegradable under AD conditions, bio-based plastic used as feedstock (kg)*
The additives impact on sustainability of organic recycling	• *Nature and impact of additives used with bio-based plastics under aerobic industrial composting and AD conditions* • η_{add} *(%) = mass of environmentally benign natural or bio-based compostable additives (kg) x 100 / mass of total additives used with the bio-based plastics during the aerobic composting process (kg)*

	• η_{add} *(%) = mass of environmentally benign natural or bio-based biodegradable under AD conditions additives (kg) x 100 / mass of total additives used with the bio-based plastics during the anaerobic digestion process (kg)*
Resources utilisation efficiency	Total water consumption efficiency • η_{water} *(kg/kg) = Total water consumption for the aerobic composting or AD process of biowaste treated together with post-consumer /industrial biodegradable bio-based plastics, accepted at a max percentage of the feedstock supply (kg/kg compost or kg/kg biogas) / Total water consumption for the aerobic composting or AD process of biowaste (kg/kg compost or kg/kg biogas)* Wastewater and rain water recirculation • η_{Rwater} *(%) = quantity of water recycled in the organic recycling process for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics (kg) x 100 / quantity of total water usage (kg)* Total energy consumption efficiency • η_{energy} *(kWh/ kWh) = Total energy consumption required for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics per unit mass of compost or biogas produced (kWh/kg) / Total energy consumption (kWh) required for the aerobic composting or AD of bio-waste per unit mass of compost or biogas produced (kWh/kg)* Renewable energy use / total energy consumption • $\eta_{Renergy}$ *(%) = kWh of energy derived from renewable sources for the aerobic composting or AD of bio-waste containing post-consumer /industrial bio-based biodegradable plastics x 100 / total kWh of energy consumption*
Waste – Emissions impact on sustainability of organic recycling	Specific gas emissions • *Specific gas emissions (kg/kg) = quantity of specific gases emitted during the organic processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced from the process (kg/kg* Residuals, solid waste • *Solid waste (kg/kg) = quantity of solid waste rejected from the organic processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced from the process (kg/kg)* Leachate or AD effluents • *Leachate (kg/kg) = quantity of leachate or effluent generated from the organic processing of bio-waste containing post-consumer /industrial bio-based compostable plastics per unit mass of compost or biogas produced from the process (kg/kg)*

3.6 Closing the biogenic carbon loop through organic recycling of post-consumer /industrial biodegradable bio-based plastics criterion

Closing the biogenic carbon loop: The produced CO_2 during the composting process and/or the AD process is released to the atmosphere and is absorbed by the plants (i.e. by the feedstock for bio-based products) closing in this way the biogenic carbon cycle. If the final compost is characterized and certified as organic fertilizer, or soil improvement compound, according to [11] then the compost/digestate partially contributes to recirculation of nutrients and the CO_2 absorption for the biomass production replacing corresponding agrochemical inputs. However, the quantity of the biomass produced from the aerobic composting or AD of biodegradable bio-based plastics is insignificant as compared to the compost quantities produced from the biowaste treated. Thus, the recirculation potential of the organic recycling of compostable post-consumer bio-based plastics is not important to be taken into consideration, in contrast to the recirculation potential of the mechanical or chemical recycling of post-consumer /industrial bio-based plastics EoL option, where the materials recovered are recirculated.

Proposed metrics: The efficiency of closing the carbon loop metric, is already addressed through the organic recycling efficiency indicator, under the corresponding common TESA-environmental criterion (Table 6).

The second proposed quantified metric for the AD of post-consumer bio-based plastics is the production of biogas and its potential use for energy generation that can be used inside the AD plant in the form renewable energy, closing the loop of biogenic carbon in another way (estimated kWh generated from biogas or biomethane produced from bio-based plastic). This possibility however, it not a preferred option for bio-based plastics. Production of renewable energy (through AD or incineration) is an inferior EoL option as compared to material recovery and should be applied only to non-recyclable bio-based plastics.

This metric, as renewable energy use/ total energy consumption, is also already addressed through the resource's utilization efficiency indicator, under the common TESA-environmental criterion (Table 6).

4 Conclusions

The bio-based plastics sector develops dynamically, and the need to investigate all the alternative preferred EoL options is imminent. The techno-economic sustainability analysis (TESA) used for the assessment of alternative EoL routes for post-consumer /industrial bio-based plastics, aims at ensuring that these specific plastic waste streams are routed to optimal EoL options, in support of the circular bioeconomy. It is important to consider the sustainability assessment methodology leading to the determination of the sustainability criteria, indicators and metrics as useful tools examining the possibilities of a specific EoL option to be feasible under the technical, economic and environmental aspects and thus subsequently specify the optimal route that will support the circular bioeconomy concept in line with sustainability consideration.

For post-consumer plastics, conventional and bio-based, biodegradable and non-biodegradable, priority, according to CEP, is the material recovery (mechanical and chemical recycling) and recirculation of materials. If material recovery, assessed by the relevant TESA criteria, is not technically feasible or economically or environmentally sustainable, then organic recycling is considered as a second EoL choice, provided that the plastics are biodegradable under the specific conditions.

Even though the contemporary quantities of (nonrecyclable) biodegradable bio-based plastics routed to aerobic composting or AD facilities, represent a very low percentage of the total bio-waste and green-waste, their organic recyclability is a major issue: The market of biodegradable biobased plastics develops rapidly (e.g.. PHAs). Banned single use conventional plastics are already replaced by biodegradable/compostable articles. Plastic bags used to collect bio-waste should also be compostable. The organic recycling industry needs to be assured that the presence of plastics in the organic waste stream will not interfere negatively with the current operating procedures.

The sustainability of organic recycling (industrial aerobic composting and AD) in treating non-recyclable biodegradable / compostable plastics should be established. For this, a set of criteria should be satisfied to assure technical feasibility, economic viability and environmental sustainability. A detailed methodological analysis of the criteria that define the technical feasibility and the economic viability of the operation (TESA) is presented. The interesting party may choose among the qualitative and quantitative indicators proposed, in conducting a TESA according to the specific conditions and scope of the analysis. It is understood that the TESA-based assessment should be accompanied by an Environmental and Social Sustainability Assessment to complete the sustainability analysis of the proposed EoL option.

Through the aerobic composting of biobased plastics (and biowaste), the closing of the carbon loop is realized, since the released CO_2 during the composting, is eventually absorbed by the plants. Production of renewable energy through AD (or incineration) is an inferior EoL option as compared to material recovery and should be applied only to non-recyclable biodegradable plastics.

Organic recycling of biodegradable polymers destroys high added value, precious polymeric materials, converting them into CO_2 and H_2O (and biogas for AD). Materials recovery remains the priority EoL option for biobased plastics. Organic recycling represents the 2nd EoL choice for nonrecyclable biodegradable bio-based plastics. Both options should meet their corresponding sustainability criteria.

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