Waste Management 201 (2025) 114786

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

The growing problem of waste bioplastics disposal, and a way to tackle it☆

Filippo Marchelli [a,b], Luca Fiori [a,c,*]

[a] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy
[b] Department of Civil, Chemical and Environmental Engineering, University of Genova, Genova, Italy
[c] Center Agriculture Food Environment (C3A), University of Trento, San Michele all'Adige, Italy

A B S T R A C T

Biodegradable plastics will grow significantly in the coming years thanks to their potential for renewability and circularity, particularly in certain European countries. Despite being a niche, their disposal is already emerging as a challenge. Insufficient public awareness is a partial cause, with people being unaware or confused on how to deal with them. Other problems are inherent to the way organic waste treatment plants work. There is indeed a stark contrast between standard biodegradability tests and actual conditions at treatment facilities, often dismissed or ascribed to the negligence of plant operators. If bioplastics are really to be deployed on a large scale, a joint technological effort is essential to properly manage their end-of-life. This contribution briefly summarises the scenario of bioplastic use in the world, the European legislation on the matter (or lack thereof), and the difficulties that waste management plants face with these materials, with a focus on a reference case – Italy – and with an international perspective. Finally, we explore how hydrothermal treatments are emerging in the scientific literature as a possible solution to some of these problems, as they can solubilise most bioplastics and facilitate their treatment in the most updated organic waste treatment plants, which couple anaerobic digestion and composting.

1. Introduction and scope

Fossil-based plastics have enhanced many aspects of our lives, and nowadays our societies could not function without plastic materials. Over the last decades though, the environmental threats that they pose have become impossible to overlook. From the perpetual extraction of oil and its purchase from questionable regimes to animals suffocating due to plastic bags, the general population is increasingly aware of the necessity to move beyond plastic items (Dilkes-Hoffman et al., 2019a). Yet, the path to achieving this goal remains elusive.

Bioplastics have recently emerged as a possible solution to some of the problems posed by fossil-based plastics. In the most common sense, the word "bioplastic" identifies a material with mechanical properties comparable to traditional plastic, but obtained from renewable sources and biodegradable. However, the term is less frequently used for material possessing only one of such features. Fostered by their environmental benefits (both real and perceived) and sometimes by legislation, bioplastics have become increasingly common in everyday life. However, this widespread adoption has already brought practical challenges.

This work aims to provide a concise overview of the challenges in waste bioplastics management. While some of the problems may stem from misunderstandings and are expectable with the adoption of a new technology, others appear inherent to these materials. Overcoming these problems necessitates open discussion to identify appropriate management practices, rather than denying or neglecting them. In this work, we focus on the case of Italy as a reference example: In Italy, legislative initiatives caused challenges to emerge more evidently than in other countries, where bioplastics are still less widespread or less efficiently collected. Finally, we discuss how the hydrothermal treatment of bioplastics has emerged in recent literature as a potential way to make bioplastics compatible with common organic waste treatment pathways.

2. Bioplastics: Production and origin

Bioplastics currently represent a niche market, accounting for about 0.5 % of total plastic production in 2022. However, their production is expected to grow significantly, with estimates predicting almost a threefold increase by 2029, reaching approximately 5.7 million tons per year (European Bioplastics e.V., 2024). Their distribution is uneven: while they are almost absent in some countries, in other countries their use is mandated for certain items, such as shopping bags in Italy.

A standardized definition of bioplastics does not exist, but the term generally refers to plastic materials that possess at least one of two qualities: being derived from biomass (bio-based) or being biodegradable. However, biodegradability is generally the main property associated with bioplastics. In fact, biodegradable bioplastics are expected to

☆ This article is part of a special issue entitled: 'Timely Advances in WM' published in Waste Management.

* Corresponding author at: Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy.
E-mail addresses: filippo.marchelli@edu.unige.it (F. Marchelli), luca.fiori@unitn.it (L. Fiori).

https://doi.org/10.1016/j.wasman.2025.114786
Received 8 November 2024; Received in revised form 24 March 2025; Accepted 2 April 2025

rise the most in the next few years, although their disposal methodology is the most unclear. Conversely, bio-based traditional plastics are chemically identical to fossil-based plastics and can follow the same treatment pathways.

The main types of biodegradable plastics are poly(lactic acid) (PLA), poly(hydroxyalkanoate) (PHA), and starch blends (SB). Although in principle they could be obtained from any type of biomass, they are currently mostly synthesised from first-generation biomass feedstocks, namely sugar- or starch-rich products. Whether the whole production of plastics could be sustainably replaced with such bioplastics without harming food chains is another debated aspect (Brizga et al., 2020), but outside the scope of this work. Table 1 summarises the principal bioplastics and their production route. More information about bioplastics producers and applications is available in other works (Mhaddolkar et al., 2024a).

3. The current challenges of waste bioplastics

Bioplastics are still rather new in our societies. It is thus to be expected that legislations and guidelines still need to fully and effectively adapt to them. In recent years however, a lack of standardisation and clear practices has emerged (Stasiškienė et al., 2022): if not properly addressed, it could undermine the adoption of these materials.

A notable issue lies in the very use of these materials. Oftentimes, they are employed to substitute fossil plastics for single-use objects: food packaging, shopping bags, tableware items, etc. Although the overall effect of this practice may be positive (and life cycle assessments should verify it), it fails to change our consumption habits regarding single-use items. The European Union (EU) Directive 2019/904 has indeed banned various types of single-use plastic items. The rationale, supported by the scientific community, is that we should as much as possible transition to reusable objects, with bioplastics only considered where recycling is unfeasible (Brizga et al., 2020; Paul-Pont et al., 2023). The legislation does not differentiate between traditional plastics and bioplastics, and this has created problems with some member states. This is the case of Italy, which adopted this normative mandating that bioplastic items are not to be considered within the single-use plastic category. The disagreement has now escalated to an infringement procedure between EU and Italy (European Commission, 2024).

Another problem lies in the incorrect perception of consumers. Surveys performed in different parts of the world pointed out that many of them are not fully aware of the unique characteristics of bioplastics or cannot distinguish them from traditional plastics (Ansink et al., 2022; Dilkes-Hoffman et al., 2019b; Mhaddolkar et al., 2024a; Mhaddolkar et al., 2024b). They may consequently discard bioplastics in the incorrect bin, creating problems to waste treating facilities. Plastic waste is primarily treated via mechanical recycling, which involves separating the conveyed items based on the constitutive polymer via gravimetric and optical methods. These systems are not designed to handle bioplastics, which can impair the overall recycling process (Staplevan et al., 2024). Some researchers argue that recycling is still the preferable route for waste bioplastics, but recycling facilities need to be adapted to accommodate them (Cristóbal et al., 2023). This would likely be economically unjustified for such unabundant materials, which would hence further populate the already sizeable unrecyclable residue (Moliner et al., 2024). Other consumers instead incorrectly interpret the biodegradability label, assuming that these materials may be treated via home composting or even discarded in the environment, where they may remain unaltered for a time comparable to traditional plastics: recent reviews (Afshar et al., 2024; Colwell et al., 2023) outlined the unclear and variable degradation behaviour of bioplastics in real world conditions. A clear and capillary divulgation is thus vital as these products become more common.

Table 1
Main bioplastic types, their origin and their response to anaerobic digestion.

Material	Main synthesis route	Response to anaerobic digestion (Bátori et al., 2018; Vardar et al., 2022)
Poly(lactic acid) (PLA)	Polycondensation of lactic acid or ring-opening polymerisation of lactide	Not degraded in the timeframe of commercial plants, both in mesophilic and thermophilic conditions
Poly (hydroxyalkanoate) (PHA)	Direct bacterial synthesis from organic matter	Degraded both in mesophilic and thermophilic conditions
Poly(butylene succinate) (PBS)	Esterification of succinic acid with 1,4-butanediol	Usually not degraded
Poly(butylene adipate terephthalate) (PBAT)	Random co-polymer obtained from adipic acid, 1,4-butanediol and dimethyl terephthalate	Usually not degraded
Starch blends	Blend of starch and plasticiser(s)	Generally not degraded in mesophilic conditions and degraded in thermophilic conditions
Cellulose acetates	Acetylation of cellulose	

Problems do not end when bioplastics reach their intended destination, which varies from territory to territory. EU legislation remains ambiguous and scattered: Mhaddolkar et al. identified 13 instances of biodegradable plastics being mentioned, of which only four detailing disposal practices (Mhaddolkar et al., 2024a): *i*) The EU Waste Framework Directive (2018) states that bioplastic packaging must be collected with biowaste; *ii*) The Guidance for separate municipal waste collection (Dubois et al., 2020) states that bioplastics can be collected with biowaste provided that they are certified as compostable and do not hinder the compost value; *iii*) The New Proposal for a Regulation on Packaging and Packaging Waste Directive (2022) and the EU policy framework on bio-based, biodegradable and compostable plastics (2022) define four types of compostable plastics that must be collected with biowaste, while the others are to be valorised through material recovery (and hence collected with plastics/packaging).

This ambiguousness has led single member states or regional authorities to define their own disposal practices. As already mentioned, the case of Italy is particularly interesting because it mandated shopping bags and many single-use objects to be made exclusively of bioplastics. This has resulted in a significant penetration in the market, and consequently in disposing facilities. In Italy, bioplastics must be collected with the organic fraction of municipal solid waste (OFMSW). OFMSW is produced in large quantities by human settlements. Starting in 2024, EU-member states are obliged to organise separate collection to ensure its proper treatment. Official quantifications of bioplastics in OFMSW is not available, but a 2020 study from two Italian consortiums indicated a 3.7 % mass fraction, which more than doubled in three years; the mass fraction of traditional plastics also increased, reaching 3.1 % (Consorzio Italiano Compostatori and Corepla, 2020). Our communications with plant managers suggest that these numbers may now be even around 5–10 %. The lack of official data is not a peculiarity of Italy: there is no specific waste category for bioplastic waste both in the EU and in the US, and consequently it is impossible to obtain statistics about their production and treatment (Briassoulis et al., 2019).

One might assume that OFMSW treatment plants would be the perfect way to dispose of bioplastics, given their compostable nature, but reality is unfortunately more complex. Bioplastics face two problems in these plants: one relating to their physical properties (size, shape, stiffness) and another to their response to biochemical treatment.

OFMSW treatment plants usually use a size-separation unit to prevent large objects from entering the bio-conversion operations. This unit targets objects that would unlikely degrade and hence clog units, such as bones, branches or incorrectly disposed plastic objects. Large bioplastic items (bags, cutlery, …) are also often caught in this pre-treatment and do not enter the plant (Dolci et al., 2023). The concurrent presence of fossil plastic items further complicates things, as it is difficult to separate them from bioplastics. The resulting mixture is then sent to other treatment methods, such as landfilling or waste incineration, which are inappropriate for bioplastics and hamper the environmental and economic sustainability of the plant. While incineration with energy recovery is not inherently inadequate for bioplastics, two issues arise in practice. First, waste bioplastics are often heavily contaminated with wet organic materials, reducing the efficiency of waste-to-energy plants. Second, if most bioplastics ultimately end up in waste-to-energy plants, their biodegradability becomes irrelevant. In fact, bio-based traditional plastics (bio-PE, bio-PET, etc…) have a higher calorific value and a lower oxygen content than most biodegradable plastics, and would behave better in thermochemical conversion processes or could enter standard recycling cycles.

Even when bioplastics manage to enter the intended treatment chain, problems can arise. The reason lies in the discrepancy between the certification tests and the actual treatment procedures. Bioplastics are usually certified as compostable according to UNI EN 13432, which requires at least a 90 % degradation of the material over a period of 6 months in industrial composting conditions. What happens in most plants is much different: the best available technique (BAT) to treat the OFMSW is nowadays recognised to be a combination of anaerobic digestion (AD) and composting. Together, they produce two valuable products—biogas and compost—and properly treat the OFMSW with overall residence times down to 1.5 months. Taking again Italy as a case study, the 7.2 Mton of OFMSW produced in 2022 were treated in 358 plants: 285 of them perform only composting, 22 only AD, and 51 employ the combined BAT process. However, the plants that employ AD (alone or in combination) are generally larger in size, and they treated about 65.5 % of the Italian OFMSW (ISPRA, 2024). Official data on the treatment method for OFMSW in EU are not available, so it is difficult to draw comparisons. A recent report by IEA Bioenergy focused on 12 countries (Gustafsson et al., 2024) and stated that China, Germany, France, Brazil and the UK are the countries with the highest numbers of biogas plants, but the vast majority of them process agricultural residues. Biogas from municipal organic waste is more than 10 % of all biogas produced only in China, Finland, Norway, Sweden and Switzerland.

AD is generally unsuitable to treat bioplastics (Dolci et al., 2023; Pangallo et al., 2023), as Table 1 reports. The reason is usually ascribed to their low hydrolysis rates, which impede all the subsequent phases. Moreover, bioplastic bags are often employed by citizens to confer organic wastes, and as a result the waste can remain trapped in the bags without getting in contact with the digester environment, thus not degrading. Clogging of some internal units may also happen in some cases. Mostly-unaltered bioplastics thus remain in the digestate and are sent to composting, but this process is also ineffective on them due to the short residence times adopted. Bioplastics eventually end up in the compost, lowering its quality and making it unsuitable for its applications: a compost with small plastic pieces (no matter if fossil-based or bio-based) is not appreciated by users and has no market. The obvious solution to such problems would be to increase the composting residence times and/or recirculate the undegraded bioplastics, but clearly it would translate in larger volumes and greater energy consumption, which may not be feasible considering the difficulties that these plants face. If traditional plastics were also present, they would be recirculated perpetually.

Considering the case of Italy, multiple reports regarding such problems were published. Oftentimes, as plant managers also confirmed to us, bioplastics are separated at the entrance of the plants and discarded (Greenpeace Italy, 2022). The most extreme case is perhaps represented by the Autonomous Province of Bolzano, in North-East Italy. Here, the local waste management authority has instructed citizens to not collect bioplastics with organic residues at all, disposing them instead together with non-recyclable waste (SEAB S.p.A., n.d) that is then sent to a waste-to-energy plant. This decision was controversial and has resulted in a lawsuit (Alto Adige, 2023). In other parts of Italy bioplastics are not banned, but citizens are still advised to use paper bags to collect organic residues, rather than bioplastic ones. This is the case of the Autonomous Province of Trento (North-East Italy), where citizens are provided with free paper bags to collect their organic residues, which are then sent to a plant based on the above-mentioned BAT scheme.

Moving away from Italy, Mhaddolkar et al. examined the legislation of 12 other EU countries, with interesting and diverse findings (Mhaddolkar et al., 2024a). In particular, Finland, Ireland, Lithuania, Luxembourg, the Netherlands, Slovenia, and Sweden do not mention biodegradable plastics in their legislation at all, with local authorities defining their own guidelines. Austria states that compostable plastics can be collected with biowaste, but local guidelines still suggest collecting them with plastics or residual waste. Denmark, France and Germany follow a similar approach, mandating that biodegradable dustbin bags are to be collected with biowaste, while the other types of biodegradable plastics with plastic waste. Apart from France (and Italy) with shopping bags, no other country has imposed the use of bioplastics for specific applications. Outside EU, the situation is similar: bioplastics are used and are in some cases encouraged by governments, but disposal pathways remain unestablished. For example, interested readers may find more information on Brazil (Lima et al., 2022), Greece (Barbir et al., 2024) Japan (Otaki and Kyono, 2022) or more generalised studies (Garrido et al., 2021; Jayakumar et al., 2023). The case of Italy thus appears particularly emblematic and possibly useful as a reference for other countries.

Even outside the waste treatment framework, the topic of bioplastics is starting to stir up controversies: one example is the actual behaviour of biodegradable mulch films employed in agriculture (Degli-Innocenti, 2024a,b; Nizzetto et al., 2024). Although, as we have mentioned, it is natural and expectable that how to deal with novel materials on a large scale remains dubious for a while, these problems need to be addressed and discussed openly and without preconceptions, rather than denied or dismissed.

In this framework, the research on bioplastics valorisation has become quite active. On the one hand, some researchers proposed modifications of bioplastics chemical structure, to make them more easily degradable (Kumar et al., 2023; Maraveas et al., 2023). On the other hand, alternative methods to valorise waste bioplastics have been proposed (Díez et al., 2023; Jiang et al., 2023; Lee et al., 2022; Sanchez-Hernandez et al., 2020; Urbanek et al., 2021). Among such methods, hydrothermal treatments stand out for their simplicity of operation and already proven effectiveness within AD plants.

4. How hydrothermal treatments may help

If we wish to keep collecting bioplastics with other organic residues (and otherwise, shifting to bio-based traditional plastics would be more reasonable), two main problems must be addressed: the mechanical features of bioplastics and their low hydrolysis rates. In the last few years, hydrothermal treatments (HTs) have emerged in the research as a possible way to overcome both problems.

HTs are industrial processes taking place in pressurised subcritical liquid water. They are generally categorised as thermal hydrolysis (performed at 140–180 °C), hydrothermal carbonization (180–250 °C) and hydrothermal liquefaction (250–370 °C). They take advantage of the high reactivity of water in these conditions and thus can operate without chemicals. Leaving aside hydrothermal liquefaction, whose purpose is creating a liquid fuel, thermal hydrolysis and hydrothermal carbonization have repeatedly been shown to be effective pretreatments for biomass prior to AD. Biomass responds to these treatments by partially hydrolysing, generating a slurry rich in dissolved organic molecules and carbonaceous solid particles. If proper severity conditions (in terms of temperature and residence time) are employed in the HT, the slurry produces biogas at higher yields and production rates in AD (Zhang et al., 2024). The application of HTs to bioplastics is more recent and the number of related studies is still scarce: Table 2

Table 2
Summary of studies dealing with the HT and anaerobic digestion of bioplastics.

Material(s)	HT operating conditions (temperature, residence time, addition of chemicals)	HT results	Anaerobic digestion results	Study
PLA (commercial cutlery, grinded)	120–240 °C 10–120 min 0–10 % of NaOH	Solubilisation: best at 200 °C for 10 min, with no NaOH. Product is acid even at high NaOH concentrations.	Much more biogas and in shorter times if HT is applied, comparable to OFMSW.	(Mu et al., 2021)
PLA (commercial, powder-form)	70–150 °C 1–48 h 0–5 % of $Ca(OH)_2$ and H_3PO_4	Solubilisation: solubilisation at 150 °C for 6 h and at 120 °C for 24 h with no $Ca(OH)_2$. Adding $Ca(OH)_2$ lowers the required severity.	Biodegradation yields of 32–73 % in 30 days of AD after HT. Best HT conditions for biogas production: 70 °C for 48 h with 2.5 % of $Ca(OH)_2$.	(Cazaudehore et al., 2022)
Five bioplastics from eyewear: cellulose acetates, starch blend, galalith, polyamide	180–220 °C 1 h	Solubilisation: moderate at 180 °C, high at 220 °C (except for polyamide).	Not tested.	(Marchelli et al., 2023b)
Cellulose acetate from eyewear, coarse blocks	180–250 °C 1 h	Solubilisation: nearly complete at 210 °C (or 190 °C with distilled water). At higher T, hydrochar production.	Much higher biogas production after HT, but maximum biodegradation is 15 %.	(Marchelli et al., 2023a, Ischia et al., 2025)
PLA, PHA, PBAT, PBS (commercial, powder-form)	100–150 °C 1–3 h	At 150 °C for 3 h: solubilisation complete for PLA, moderate for PHA and PBS, null for PBAT.	Higher biogas yields in all cases after HT; PHA shows good biodegradation even without HT, while PBAT shows scarce biodegradation even with HT.	(Im et al., 2024)
Cellulose acetate from eyewear (commercial, powder-form)	190–250 °C ⅙-4h	Solubilisation: maximum at 210 °C for 1 h. Degradation achievable at all temperatures with adequate residence times.	Not tested.	(Bracciale et al., 2024)
Two types of commercial PLA granules	21–160 °C 1–72 h 0–6 M of KOH	Solubilisation: unachievable at all tested temperatures without KOH addition. The more KOH is added, the less severe the process needs to be. The two PLAs behave differently.	Methane yield approaches the maximum theoretical value if PLA is solubilised. K^+ concentration is high but does not inhibit the bacterial activity.	(Vasmara et al., 2024)
Commercial PLA granules	160–240 °C 1 h	PLA is hydrolysed and various compounds form, but quantitative yields are not reported.	Highest biomethane increase (21.4-fold, compared to the untreated material) after a 180 °C HT.	(Wang et al., 2024)
PLA (pure lab-grade and commercial spoons) and Mater-Bi® (commercial forks, mixture of PLA and PBS)	160–200 °C 1 h	Solubilisation: partial at 160 °C and complete at 180 and 200 °C. The liquid phase consists of monomers and oligomers.	The biomethane yields from both bioplastic items increase dramatically if HT is employed, approaching their theoretical maxima. The best HT temperature depends on the inoculum and bioplastic.	(Marchelli et al., 2024, Ferrentino et al., 2025)
Two biodegradable bags consisting of PLA, PBAT and starch, mixed with OFMSW.	80–120 °C 1 h	Not commented separately.	Best biogas yield increase (23.5 %) obtained after an 80 °C HT, while a 120 °C HT has a negative effect. One of the two bioplastics originates a phytotoxic digestate.	(Shao et al., 2025)

summarises their focuses and findings.

Despite their preliminary nature, the studies seem to agree that the treatment is beneficial, being able to at least disintegrate bioplastic products, thus solving the clogging problem. When the obtained products are sent to AD, an enhancement of their behaviour is observed as well: bioplastics decomposition and biogas production both increase. The hydrothermal pretreatment solves the problem of the scarce biogas production. The 'forced' hydrolysis seems the key to explain this enhancement, as the inability of bacteria to hydrolyse bioplastics is often cited as the bottleneck that impedes the whole degradation process.

Clearly, more studies are needed before a full understanding of the process can be achieved. The available studies (Table 2) present some discrepancies in terms of the minimum temperature required to hydrolyse the materials, possibly due to the different physical shape, crystallinity and additives of the employed feedstocks. For PLA, the studies that employ a standard 1 h residence time generally indicate that at least 180 °C are necessary for an effective degradation. Among the existing research gaps we can cite that most studies dealt with PLA and that almost all of them were performed in rather ideal conditions, i.e. employing only bioplastics and water. In a real scenario, we expect that the bioplastics sent to this pre-treatment will contain a large quantity of other organic residues and, quite likely, also some fossil plastics. We hence recommend performing additional studies considering real or realistic mixtures of bioplastics and organic waste. Experimental campaigns should also mimic what would happen industrially, avoiding steps that would not be performed in a real process. Among these are the fine grinding of the bioplastics or the use of distilled water, which can lower the degradation temperature (Ischia et al., 2025; Marchelli et al., 2023a). Some of the studies (and also others that are out of the scope of this work) indicate that the use of bases is also quite effective in hydrolysing bioplastics (García-Depraect et al., 2023), markedly decreasing the severity needed for an effective degradation. However, the use of bases would require a continuous need for chemicals and the establishment of more corrosive conditions, so their use should be carefully evaluated. Conversely, the advantage of increasing the pH of the slurry fed to AD does not seem very marked, considering that biogas production seems very good even when acid slurries are fed to AD.

Fig. 1 sums up the discussion by schematising what currently frequently happens in OFMSW treatment plants and illustrates a possible new scheme in which a hydrothermal treatment is integrated. The advantages of creating a more circular approach are clear, but some questions remain open and should be the focus of future research. One of these is the choice of the optimal HT operating conditions and the possible addition of chemicals, which will likely be case-dependent. To optimise resource use, the HT should also be performed with recycled process water, which is usually available in these plants, but whose use

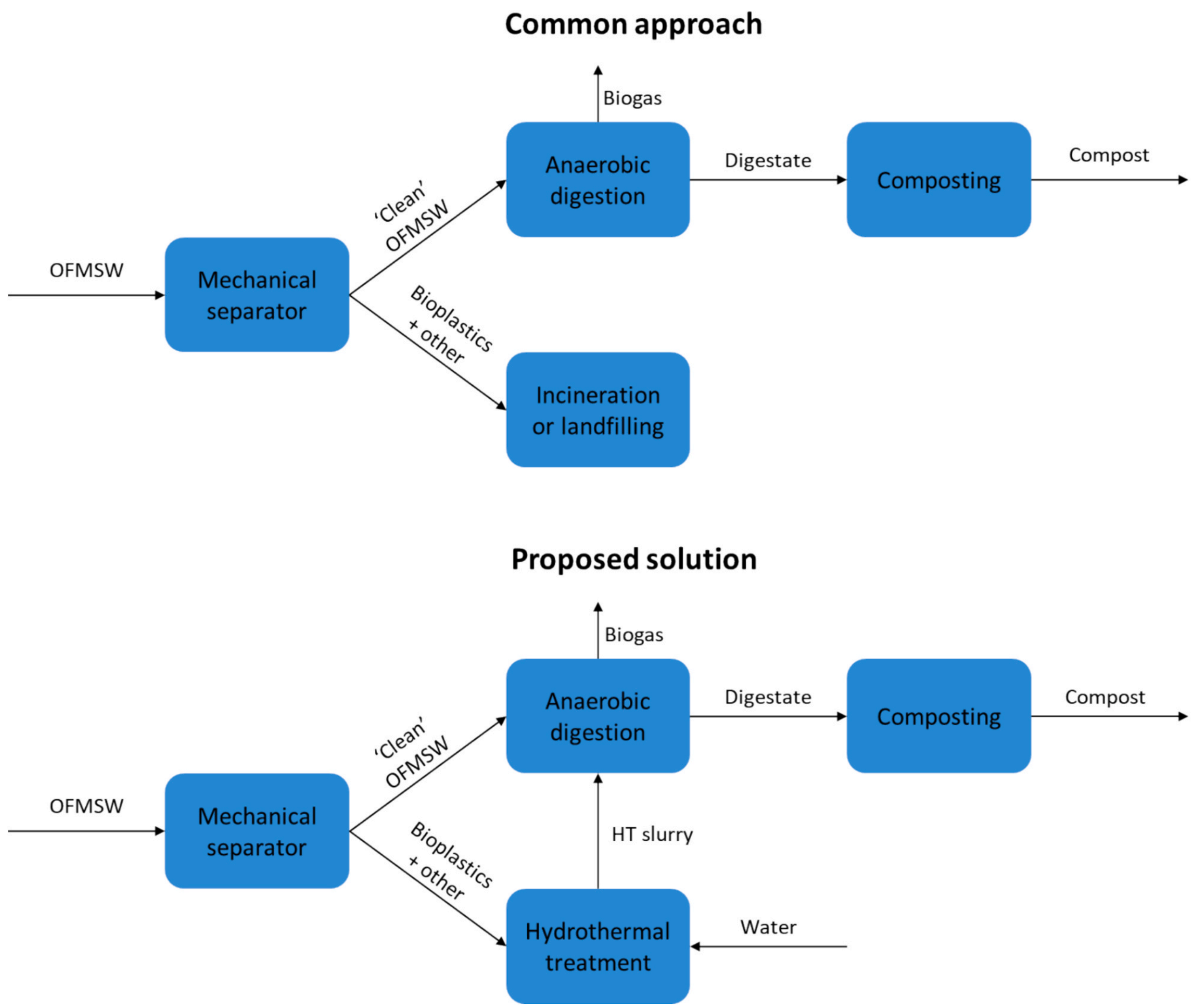

Fig. 1. Current common approach in the treatment of OFMSW containing bioplastics (above) and a possible solution featuring a hydrothermal treatment (below).

should be investigated. The use of the HT slurry for more advanced applications, such as the extraction of chemicals, could also be interesting and worthy of investigation. The presence of traditional plastics could be problematic, and its effects should be assessed, also considering the possible generation of microplastics and micro-bioplastics (Piyathilake et al., 2024). Finally, the effectiveness of this solution must be evaluated through economic and life cycle assessments. These analyses should determine whether the benefits—such as reducing residues that require external disposal, minimising additional transport emissions, and potentially avoiding methane emissions from landfills—outweigh the cost and impacts of introducing a new process unit. Some of the studies of Table 2 pointed out that the increased biomethane production could offset the energy needs of the HT, but clearly this must be assessed in more realistic conditions.

5. Conclusions

Bioplastics production rates is growing significantly, but citizens, legislation, and waste treatment chains are not fully aware and accustomed to them. This has led to malpractices and inefficiencies, particularly evident in Italy where the market penetration of bioplastic is high. While systemic changes are needed, the scientific community is starting to point out that hydrothermal treatments may be a valid option to overcome some of the problems faced in waste bioplastics management. More studies, performed in more realistic conditions, are however vital for the actual deployment of this technology applied to bioplastics.

While new technologies and materials are being developed, it is essential to implement policies that maximise the benefits of bioplastics. Regarding this, the authors suggest the following recommendations to help driving the management of bioplastic waste: *i*) Discouraging the use of single-use items whenever possible; *ii*) Ensuring that citizens are well-informed about proper disposal practices; *iii*) Promoting biobased traditional bioplastics (bio-PE, bio-PET, etc…) which would allow us to free ourselves from the use of fossil sources (thus avoiding introducing additional carbon into the biosphere and/or the atmosphere) and which could be recycled together with traditional fossil-based plastics; *iiii*) Promoting biodegradable bioplastics only in cases where they will likely be highly contaminated by organic waste—making mechanical recycling unfeasible; in this case their end-of-life would be the same as organic waste and OFMSW, and improvements would need to be made on waste management plants and practices, e.g., the use of hydrothermal technology to promote bioplastic hydrolysis and biomethane production, or the increase in the bioplastic composting time to allow their conversion into compost, in particular in the most updated plants coupling anaerobic digestion and composting.

CRediT authorship contribution statement

Filippo Marchelli: Writing – original draft, Visualization, Project administration, Conceptualization. **Luca Fiori:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Acknowledgments

The publication was created with the co-financing of the European Union – FSE-REACT-EU, PON Research and Innovation 2014-2020 DM1062/2021.

Data availability

No data was used for the research described in the article.

References

Afshar, S.V., Boldrin, A., Astrup, T.F., Daugaard, A.E., Hartmann, N.B., 2024. Degradation of biodegradable plastics in waste management systems and the open environment: A critical review. J. Clean. Prod. 434, 140000. https://doi.org/10.1016/j.jclepro.2023.140000.

Alto Adige, 2023. Rifiuto umido, c'è il mega ricorso [WWW Document]. URL https://www.altoadige.it/cronaca/rifiuto-umido-c-è-il-mega-ricorso-1.3648916 (accessed 2.19.24).

Ansink, E., Wijk, L., Zuidmeer, F., 2022. No clue about bioplastics. Ecol. Econ. 191, 107245. https://doi.org/10.1016/j.ecolecon.2021.107245.

Barbir, J., Lingos, A., Foschi, E., Stasiskiene, Z., Skanavis, C., Fletcher, C., Leal Filho, W., 2024. Assessing the readiness of Greek municipalities to manage bioplastics in municipal waste management streams. Discov. Sustain. 5, 1–15. https://doi.org/10.1007/S43621-024-00428-7.

Bátori, V., Åkesson, D., Zamani, A., Taherzadeh, M.J., Sárvári Horváth, I., 2018. Anaerobic degradation of bioplastics: A review. Waste Manag. 80, 406–413. https://doi.org/10.1016/j.wasman.2018.09.040.

Bracciale, M.P., de Caprariis, B., Musivand, S., Damizia, M., De Filippis, P., 2024. Chemical Recycling of Cellulose Acetate Eyewear Industry Waste by Hydrothermal Treatment. Ind. Eng. Chem. Res. 63, 5078–5088. https://doi.org/10.1021/acs.iecr.3c04162.

Briassoulis, D., Pikasi, A., Hiskakis, M., 2019. End-of-waste life: Inventory of alternative end-of-use recirculation routes of bio-based plastics in the European Union context. Crit. Rev. Environ. Sci. Technol. 49, 1835–1892. https://doi.org/10.1080/10643389.2019.1591867.

Brizga, J., Hubacek, K., Feng, K., 2020. The Unintended Side Effects of Bioplastics: Carbon, Land, and Water Footprints. One Earth 3, 45–53. https://doi.org/10.1016/j.oneear.2020.06.016.

Cazaudehore, G., Guyoneaud, R., Vasmara, C., Greuet, P., Gastaldi, E., Marchetti, R., Leonardi, F., Turon, R., Monlau, F., 2022. Impact of mechanical and thermo-chemical pretreatments to enhance anaerobic digestion of poly(lactic acid). Chemosphere 297, 133986. https://doi.org/10.1016/j.chemosphere.2022.133986.

Colwell, J., Pratt, S., Lant, P., Laycock, B., 2023. Hazardous state lifetimes of biodegradable plastics in natural environments. Sci. Total Environ. 894, 165025. https://doi.org/10.1016/j.scitotenv.2023.165025.

Consorzio Italiano Compostatori, Corepla, 2020. Studio CIC – COREPLA 2020: triplicano le bioplastiche compostabili nella raccolta dell'organico [WWW Document]. URL https://www.compost.it/wp-content/uploads/2020/07/CS-4-Studio-CIC-COREPLA-2020_-raddoppiano-le-bioplastiche-compostabili-nella-raccolta-dell'organico-5.pdf (accessed 2.19.25).

Cristóbal, J., Federica Albizzati, P., Giavini, M., Caro, D., Manfredi, S., Tonini, D., 2023. Management practices for compostable plastic packaging waste: Impacts, challenges and recommendations. Waste Manag. 170, 166–176. https://doi.org/10.1016/j.wasman.2023.08.010.

Degli-Innocenti, F., 2024a. The pathology of hype, hyperbole and publication bias is creating an unwarranted concern towards biodegradable mulch films. J. Hazard. Mater. 463, 132923. https://doi.org/10.1016/j.jhazmat.2023.132923.

Degli-Innocenti, F., 2024b. Rebuttal of the arguments put forward in the Letter to the Editor by Nizzetto et. Mater 467, 133691. https://doi.org/10.1016/j.jhazmat.2024.133691.

Díez, A.M., Licciardello, N., Koleńko, Y.V., 2023. Photocatalytic processes as a potential solution for plastic waste management. Polym. Degrad. Stab. 215, 110459. https://doi.org/10.1016/j.polymdegradstab.2023.110459.

Dilkes-Hoffman, L., Ashworth, P., Laycock, B., Pratt, S., Lant, P., 2019a. Public attitudes towards bioplastics – knowledge, perception and end-of-life management. Resour. Conserv. Recycl. 151, 104479. https://doi.org/10.1016/j.resconrec.2019.104479.

Dilkes-Hoffman, L.S., Pratt, S., Laycock, B., Ashworth, P., Lant, P.A., 2019b. Public attitudes towards plastics. Resour. Conserv. Recycl. 147, 227–235. https://doi.org/10.1016/j.resconrec.2019.05.005.

Dolci, G., Rigamonti, L., Grosso, M., 2023. The challenges of bioplastics in waste management. Waste Manag. Res. J. a Sustain. Circ. Econ. 41, 1281–1282. https://doi.org/10.1177/0734242X231181999.

Dubois, M., Sims, E., Moerman, T., Watson, D., Bauer, B., Bel, J.-B., Mehlhart, G., 2020. Guidance for separate collection of municipal waste. Publications Office of the European Union. doi: 10.2779/691513.

European Bioplastics e.V., 2024. BIOPLASTICS MARKET DEVELOPMENT UPDATE 2023 [WWW Document]. URL https://www.european-bioplastics.org/bioplastics-market-development-update-2023-2/ (accessed 7.19.24).

European Commission, 2024. May infringements package: key decisions [WWW Document]. URL https://ec.europa.eu/commission/presscorner/detail/en/inf_24_2422 (accessed 2.19.25).

Ferrentino, R., Marchelli, F., Bevilacqua, A., Fiori, L., Andreottola, G., 2025. Hydrothermal pre-treatments can make PLA and PBS bioplastics suitable for anaerobic digestion. J. Environ. Chem. Eng. 13, 116204. https://doi.org/10.1016/j.jece.2025.116204.

García-Depraect, O., Lebrero, R., Martínez-Mendoza, L.J., Rodriguez-Vega, S., Aragão Börner, R., Börner, T., Muñoz, R., 2023. Enhancement of biogas production rate from bioplastics by alkaline pretreatment. Waste Manag. 164, 154–161. https://doi.org/10.1016/j.wasman.2023.04.009.

Greenpeace Italy, 2022. Altro che compost! [WWW Document]. URL https://www.greenpeace.org/italy/rapporto/15994/plastica-compostabile-difficile-degradi-negli-impianti-dellumido-altro-che-compost/ (accessed 2.19.25).

Gustafsson, M., Meneghetti, R., Souza Marques, F., Trim, H., Dong, R., Al Saedi, T., Rasi, S., Thual, J., Kornatz, P., Wall, D., Berntsen, C., Saxegaard, S., Lyng, K.A., Nägele, H. J., Heaven, S., Bywater, A., 2024. A perspective on the state of the biogas industry in 12 member countries of IEA Bioenergy Task 37.

Garrido, R., Cabeza, L.F., Falguera, V., 2021. An Overview of Bioplastic Research on Its Relation to National Policies. Sustainability 13, 7848. https://doi.org/10.3390/su13147848.

Im, S., Hwang, I., Weonjae, K., Kim, D.-H., Kang, J.-H., Kang, S., 2024. Enhancing methane production potential of biodegradable plastics by hydrothermal pretreatment. Environ. Technol. Innov. 34, 103599. https://doi.org/10.1016/j.eti.2024.103599.

Ischia, G., Marchelli, F., Bazzanella, N., Ceccato, R., Calvi, M., Guella, G., Gioia, C., Fiori, L., 2025. Cellulose Acetates in Hydrothermal Carbonization: A Green Pathway to Valorize Residual Bioplastics. ChemSusChem 18. https://doi.org/10.1002/cssc.202401163.

ISPRA, 2024. Catasto Nazionale Rifiuti, 2022 [WWW Document]. URL https://www.catasto-rifiuti.isprambiente.it/index.php?pg=gestnazione&aa=2022&regid=&mappa=0&width=1920&height=1080 (accessed 2.19.25).

Jayakumar, A., Radoor, S., Siengchin, S., Shin, G.H., Kim, J.T., 2023. Recent progress of bioplastics in their properties, standards, certifications and regulations: A review. Sci. Total Environ. 878, 163156. https://doi.org/10.1016/J.SCITOTENV.2023.163156.

Jiang, X., Bi, D., Cheng, Y., Wang, S., Peng, B., Shen, H., Zhang, T., Xia, X., Shen, Z., Zhang, Y., 2023. Enzyme pretreatments for anaerobic co-digestion of food waste blended with bioplastics: effects on methane production and microbial community structure. New J. Chem. 47, 20846–20858. https://doi.org/10.1039/D3NJ02505E.

Kumar, V., Krishna, S., Tsouko, E., Maina, S., Pandey, M., Umesh, M., Singhal, B., Sharma, N., Awasthi, M.K., Andler, R., Jayaraj, I., Yuzir, A., 2023. Commercialization potential of agro-based polyhydroxyalkanoates biorefinery: A technical perspective on advances and critical barriers. Int. J. Biol. Macromol. 234, 123733. https://doi.org/10.1016/j.ijbiomac.2023.123733.

Lee, S., Lee, J., Park, Y.-K., 2022. Simultaneous Upcycling of Biodegradable Plastic and Sea Shell Wastes Through Thermocatalytic Monomer Recovery. ACS Sustain. Chem. Eng. 10, 13972–13979. https://doi.org/10.1021/acssuschemeng.2c04050.

Lima, L.R., Gutierrez, R.F., Cruz, S.A., 2022. Challenges in the context of single-use plastics and bioplastics in Brazil: A legislative review. Waste Manag. Res. J. A Sustain. Circ. Econ. 40, 998–1006. https://doi.org/10.1177/0734242X211055548.

Maraveas, C., Kotzabasaki, M.I., Bartzanas, T., 2023. Intelligent technologies, enzyme-embedded and microbial degradation of agricultural plastics. AgriEngineering 5, 85–111. https://doi.org/10.3390/agriengineering5010006.

Marchelli, F., Ferrentino, R., Ischia, G., Calvi, M., Andreottola, G., Fiori, L., 2023a. Valorisation of eyewear bioplastics through HTC and anaerobic digestion: preliminary results. Detritus 23, 35–42. https://doi.org/10.31025/2611-4135/2023.18275.

Marchelli, F., Ischia, G., Calvi, M., Fiori, L., 2023b. Hydrothermal carbonization as a process to facilitate the disposal of bioplastics. Chem. Eng. Trans. 99, 79–84. https://doi.org/10.3303/CET2399014.

Marchelli, F., Mattonai, M., Ferrentino, R., La Nasa, J., Pecorelli, N., Modugno, F., Andreottola, G., Ribechini, E., Fiori, L., 2024. Fostering bioplastics circularity through hydrothermal treatments: degradation behavior and products. ACS Sustain. Chem. Eng. 12, 9257–9267. https://doi.org/10.1021/acssuschemeng.4c02174.

Mhaddolkar, N., Astrup, T.F., Tischberger-Aldrian, A., Pomberger, R., Vollprecht, D., 2024a. Challenges and opportunities in managing biodegradable plastic waste: A review. Waste Manag. Res. J. A Sustain. Circ. Econ. doi: 10.1177/0734242X241279902.

Mhaddolkar, N., Lodato, C., Tischberger-Aldrian, A., Vollprecht, D., Fruergaard Astrup, T., 2024b. Biodegradable plastics – Where to throw? A life cycle assessment of waste collection and management pathways in Austria. Waste Manag. 190, 578–592. https://doi.org/10.1016/j.wasman.2024.10.018.

Moliner, C., Pasquale, G., Arato, E., 2024. Municipal Plastic Waste Recycling through Pyrogasification. Energies 17, 1206. https://doi.org/10.3390/en17051206.

Mu, L., Zhang, L., Ma, J., Zhu, K., Chen, C., Li, A., 2021. Enhanced biomethanization of waste polylactic acid plastic by mild hydrothermal pretreatment: Taguchi orthogonal optimization and kinetics modeling. Waste Manag. 126, 585–596. https://doi.org/10.1016/j.wasman.2021.03.044.

Nizzetto, L., Binda, G., Hurley, R., Baann, C., Selonen, S., Velmala, S., van Gestel, C.A.M., 2024. Comments to "Degli-Innocenti, F. The pathology of hype, hyperbole and publication bias is creating an unwarranted concern towards biodegradable mulch films" [J. Hazard. Mater. 463 (2024) 132923]. J. Hazard. Mater. 471, 133690. https://doi.org/10.1016/j.jhazmat.2024.133690.

Otaki, Y., Kyono, T., 2022. Effects of information provision on public attitudes toward bioplastics in Japan. Front. Sustain. 3. https://doi.org/10.3389/frsus.2022.927857.

Pangallo, D., Gelsomino, A., Fazzino, F., Pedullà, A., Calabrò, P.S., 2023. The fate of biodegradable plastic during the anaerobic co-digestion of excess sludge and organic fraction of municipal solid waste. Waste Manag. 168, 98–106. https://doi.org/10.1016/j.wasman.2023.05.053.

Paul-Pont, I., Ghiglione, J.F., Gastaldi, E., Ter Halle, A., Huvet, A., Bruzaud, S., Lagarde, F., Galgani, F., Duflos, G., George, M., Fabre, P., 2023. Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life. Waste Manag. 157, 242–248. https://doi.org/10.1016/J.WASMAN.2022.12.022.

Piyathilake, U., Lin, C., Bolan, N., Bundschuh, J., Rinklebe, J., Herath, I., 2024. Exploring the hidden environmental pollution of microplastics derived from bioplastics: a review. Chemosphere 355. https://doi.org/10.1016/j.chemosphere.2024.141773.

Sanchez-Hernandez, J.C., Capowiez, Y., Ro, K.S., 2020. Potential use of earthworms to enhance decaying of biodegradable plastics. ACS Sustain. Chem. Eng. 8, 4292–4316. https://doi.org/10.1021/acssuschemeng.9b05450.

SEAB S.p.A., n.d. Rifiuti organici | SEAB Bolzano/Bozen [WWW Document]. URL https://www.seab.bz.it/it/imprese/rifiuti-organici (accessed 2.19.25).

Shao, H., Yu, M., Zhao, L., Wang, P., Meng, X., Ren, L., 2025. Impact of hydrothermal pretreatment on enhancing anaerobic co-digestion of food waste and biodegradable plastics. J. Environ. Chem. Eng. 13, 115205. https://doi.org/10.1016/J.JECE.2024.115205.

Staplevan, M.J., Ansari, A.J., Ahmed, A., Hai, F.I., 2024. Impact of bioplastic contamination on the mechanical recycling of conventional plastics. Waste Manag. 185, 1–9. https://doi.org/10.1016/j.wasman.2024.05.028.

Stasiškienė, Ž., Barbir, J., Draudvilienė, L., Chong, Z.K., Kuchta, K., Voronova, V., Leal Filho, W., 2022. Challenges and Strategies for Bio-Based and Biodegradable Plastic Waste Management in Europe. Sustainability 14, 16476. https://doi.org/10.3390/su142416476.

Urbanek, A.K., Strzelecki, M.C., Mirończuk, A.M., 2021. The potential of cold-adapted microorganisms for biodegradation of bioplastics. Waste Manag. 119, 72–81. https://doi.org/10.1016/j.wasman.2020.09.031.

Vardar, S., Demirel, B., Onay, T.T., 2022. Degradability of bioplastics in anaerobic digestion systems and their effects on biogas production: a review. Rev. Environ. Sci. Biotechnol. 21, 205–223. https://doi.org/10.1007/S11157-021-09610-Z/FIGURES/2.

Vasmara, C., Cazaudehore, G., Ceotto, E., Marchetti, R., Sambusiti, C., Monlau, F., 2024. Alkali, thermal, or thermo-alkali pre-treatment to improve the anaerobic digestion of poly(lactic acid)? Water Res. 258, 121744. https://doi.org/10.1016/j.watres.2024.121744.

Wang, X., Sun, Y., Liu, M., You, G., Fan, T., Wu, H., Xu, L., Zhao, X., Ma, D., 2024. Hydrothermal processing of polylactic acid: analysis of intermediate products and toxicity evaluation of anaerobically digestated residues. Chem. Eng. J. 502, 157634. https://doi.org/10.1016/J.CEJ.2024.157634.

Zhang, C., Rahnuma, K., Hou, L., Liu, X., Tang, Y., Pavlostathis, S.G., 2024. Energy and economic assessment of hydrothermal-treatment-coupled anaerobic digestion. Renew. Sustain. Energy Rev. 202, 114674. https://doi.org/10.1016/j.rser.2024.114674.