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Towards Sustainable Processing Of Municipal Household Organic Waste: The Role Of Energy Mix Grids

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ABSTRACT

The reduction and recovery of organic fraction of municipal solid waste is a major challenge for contemporary society. It requires the establishment of regional strategies with minimized environmental impact. This study employs life cycle assessment to evaluate the respective environmental performances of the current French system based on incineration, and those of alternative systems including (i) anaerobic digestion with composting and (ii) composting for biowaste treatment under different energy scenarios. The environmental impacts of Parisian biowaste are calculated by considering incineration technologies in the area, the French energy mix in 2022, the average European energy mix in 2022 and the projected French energy mix for 2030. The results show that the proportion of fossil-based sources in the energy mixes significantly influences the environmental performance of waste management systems. Energy mixes based in high-carbon fossil sources dependency tend to favour incineration-based processing systems. This is driven by the significant volume of credits allocated to the alternative energy produced from waste treatment. It is therefore essential for processing system design projects to account for planned changes in the energy mix in order to accurately assess the future impact of waste management strategies.

Keywords: Life Cycle Analysis, Biowaste, Circular Bioeconomy, Composting, Anaerobic Digestion, Energy Efficiency, Municipal Household Waste Management.

INTRODUCTION

The significance of waste management in European legislation reflects the environmental challenges posed by the vast quantities of waste requiring treatment. Annually, more than 2 billion tonnes of municipal solid waste are generated, with 32-34% comprising the organic fraction of municipal solid waste (OFMSW) in Europe [1,2]. To address the critical need for sustainable management of organic solid waste, several studies [3-5] have examined the environmental assessment of various technological alternatives that can be mobilised for this purpose. Previous research has highlighted the sensitivity of the environmental performance of biowaste reprocessing technologies to energy mixes.

Slorach et al. [3] compared incineration, composting and anaerobic digestion technologies for food waste in the United Kingdom (UK). Their study showed better environmental performance for the anaerobic digestion

treatment with a particular sensitivity of the results to the energy mix. They found out that when anaerobic digestion and incineration are credited with displacing wind or solar energy, both treatment options become net contributors to Global Warming Potential and Fossil Depletion, as the associated credits are lower compared to those for the grid electricity. As highlighted by Soimakallio et al. [4] differences in actual research questions, methodological choices, and data set selection have a significant impact on the outcomes of life cycle assessment (LCA) studies for energy systems. These inconsistencies make it challenging to compare the findings of various studies and may lead to uncertainties in the conclusions. These results were confirmed by Dastjerdi et al. [5] in a systematic review. The article states that one of the most investigated sources of uncertainty was the source of avoided electricity and assumptions for energy recovery.

The aim of this work is to assess the environmental performance of current and potential systems for

managing OFMSW in the Parisian region. To the best of our knowledge, the case of France has not been studied from this perspective. The scenarios evaluated are mainly incineration, composting, and anaerobic digestion with composting (AD-co). In the first part, the comparison of the French and European scenarios was evaluated. In the second part of this work, the influence of the energy mix planned in France for 2030 vs. that of 2022 on the

environmental performance of the OFMSW treatment system was studied. Results aim to provide actionable insights to policymakers and waste management operators.

METHODOLOGY

Figure 1 illustrates the perimeter of the data used in

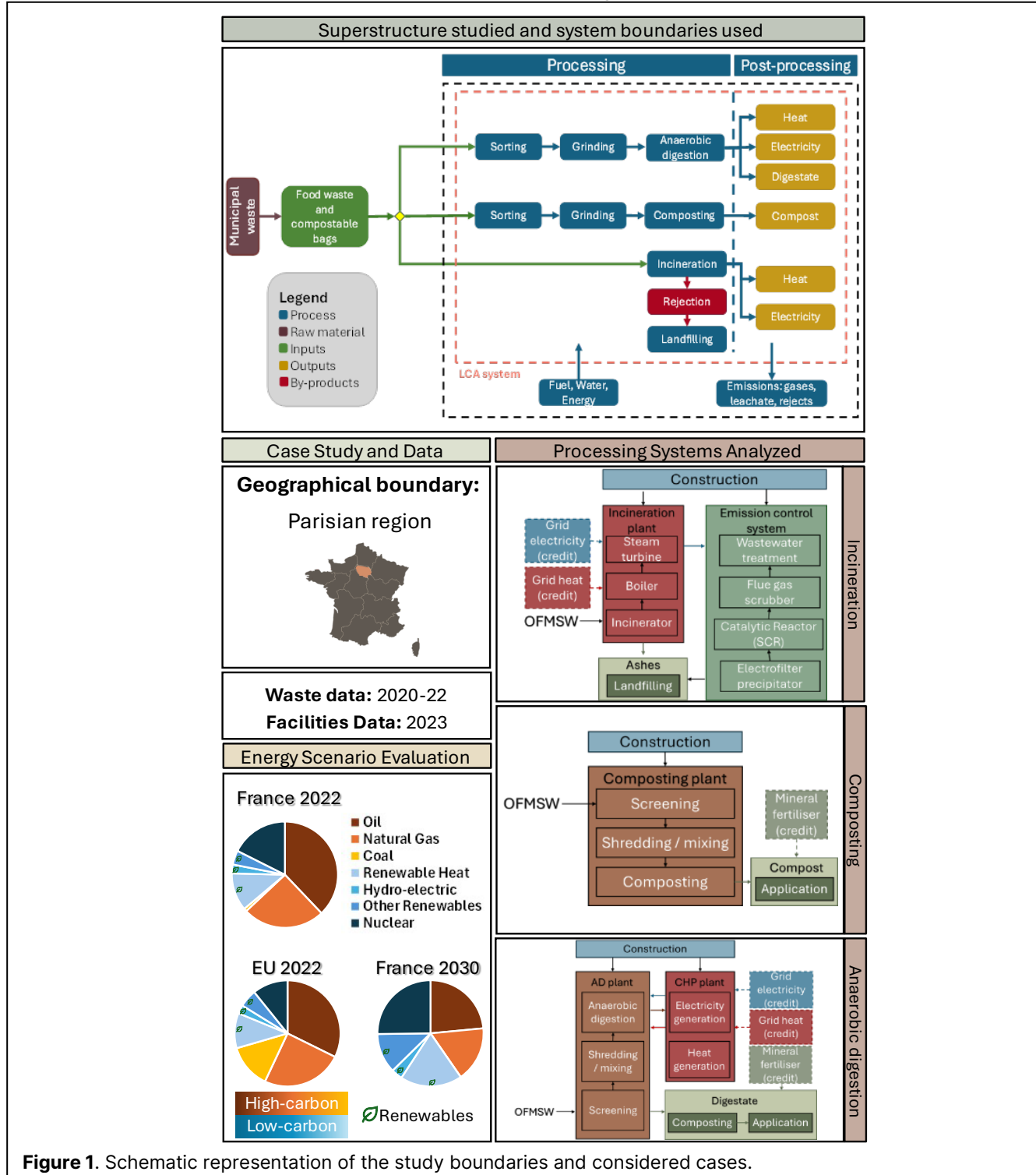


Figure 1. Schematic representation of the study boundaries and considered cases.

this study, including energy mix scenarios and the perimeters of the global system and sub-systems compared. LCA was conducted using the OpenLCA 2.3.1 software with the Ecoinvent 3.9.1 database. The four phases of LCA have been followed as standardized by ISO 14040/44. The functional unit was defined as the treatment of 1 kg of OFMSW. A review of recent publications [5–8] guided the selection of the 12 most relevant environmental categories for this field as shown in Figure 2. Impacts were normalized according to the highest absolute value per category for better visibility. The impact assessment method chosen is: ReCiPe (H) 2016 [6] (LCIA method 2.1.1).

For the analysis, three energy mixes were considered: i) France 2022 (current energy mix), ii) 2030 future scenario (projected energy mix), and iii) Average European Union (EU) energy mix in 2022 (as the comparison system). The details of these energy mixes are provided in the supplementary material (Tab. S1–3). To isolate the impact of the national energy grids, including the expected changes in the national energy grid for 2030, consistent process efficiencies have been applied throughout the study for the same technologies across all scenarios. This approach ensures that the analysis focuses solely on the influence of the different energy mix grids analysed. The Parisian OFMSW was characterised in terms of volume using data supplied by the operator, and its composition was established using literature data on composition [7]. A detailed description can be found in Tab. S4–5.

The incineration process of OFMSW was simulated using the modelling tools provided by Doka et al. [8]. After data collection, the detailed Parisian plant inventories have been summarized in Tab. S4 and used in the assessment. It is important to note that incineration facilities in Paris are highly optimized, including their dry ash treatment. The energy produced by incineration has been discounted from the LCA as a credit.

For the composting process, the inventory was retrieved from Lu et al. [9]. The compost has been allocated by means of substitution and the system is credited against the avoided production of mineral nitrogen (calcium ammonium nitrate), phosphate (diammonium phosphate) and potassium fertilizer. For that, the characterization of the compost composition was performed as proposed by Boldrin et al. [10] and detailed in Tab. S6. To credit the various fertilizer substitutions used in the study, the replaced quantity was calculated using Eq. S1–3.

For the anaerobic digestion process, the inventory was retrieved from the literature [11]. Using annual OFMSW production data for greater Paris, the required sizes for the AD-co and Combined Heat and Power (CHP) unit were calculated using the Ecoinvent inventory and scaled up with Eq. 1.

$$E_2 = E_1 \left(\frac{C_2}{C_1}\right)^{0.6} \quad (1)$$

where:

E_1 environment impact of the smaller plant

E_2 environment impact of the larger plant

C_1 plant capacity of the smaller plant

C_2 plant capacity of the larger plant.

The produced biogas, without upgrade to biomethane, has been considered to be burned in a CHP unit. Its calorific value was credited for the energy displaced, and the digestate through Eq. S4–6.

RESULTS AND DISCUSSION

The results clearly highlight the significant influence of the different energy mix grids on the environmental performance of waste treatment system.

Figure 2a and 2b illustrate the midpoint impact assessment of the studied technologies. These graphs were constructed by subtracting the environmental credits (avoided impacts) of each technology from their generated impacts. Figure 2a compares the midpoint impact assessment of the three technologies for the French (2022) and average EU (2022) energy grid mixes. Concerning fossil resource scarcity (FRS), the energy credits from displacement are sufficient to make incineration and AD-co net negative-impact processes under the studied grid mixes (60% fossil for France, 70% for the EU). This is due to energy production rates of 0.81 kWh/FU for incineration and 0.753 kWh/FU for AD-co. Incineration emerges as the best option, followed by AD-co, with a greater relative benefit in the EU context. Composting, which consumes resources like fuel and energy, does not gain sufficient offset from fertilizer displacement, resulting in a net environmental impact.

Aquatic environmental impacts, including freshwater ecotoxicity (FWEc), eutrophication (FWEu), and marine ecotoxicity (MEc), vary significantly across different contexts. In France, AD-co consistently performs best, while composting ranks as intermediate. Incineration exhibits the highest impacts due to the release of toxic compounds from combustion, flue gas washing, and phosphate emissions from fly ash. In the EU context, similar trends are observed for ecotoxicity. However, freshwater eutrophication improves substantially for incineration (-581%) and AD-co (-311%), which is attributed to the displacement of coal-based energy production.

For global warming (GW) it can be seen that incineration is the least polluting option, followed by AD-co and lastly, composting. For France and the EU, a difference of -12.16 and -13.72% is observed for incineration and anaerobic digestion respectively. It's important to point out that even if seemingly small, this difference in the impact for one kg when related to the annual production of 440kt in France creates a difference of 2 million

CO₂eq. saved per year for the incineration and 1.85 CO₂eq. for anaerobic digestion.

Human health impacts, measured through carcinogenic (HCT) and non-carcinogenic toxicity (HNCT) (1,4-DCB eq. and kg NO_x-eq.), show that AD-co consistently demonstrates superior performance, while incineration

ranks lowest despite filtration systems, due to combustion-generated toxic compounds.

For ozone formation related impacts (OF-HH and OF-TE), composting presented the highest impact due to unfiltered NO_x and NMVOC emissions, with the lack of biofilters resulting in direct atmospheric exchange of

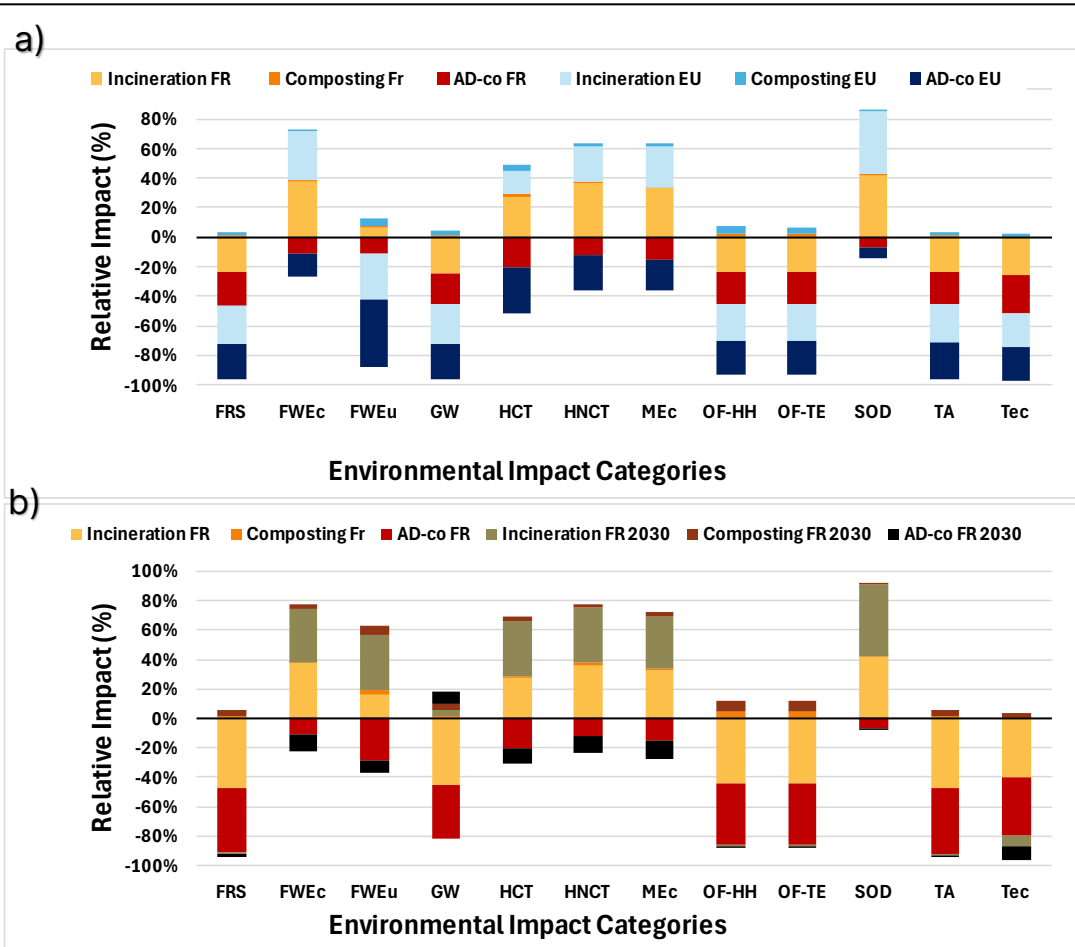


Figure 2. Environmental impacts with credits of the various processing technologies in the Parisian region a) using the French (2022) and European (2022) energy mix and b). using the current (2022) and projected French (2030) energy mix Terrestrial Acidification (TA), Global Warming (GW), Stratospheric Ozone Depletion (SOD), Ozone formation-Human health (OF-HH), Ozone formation-Terrestrial ecosystems (OF-TE), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Freshwater Eutrophication (FWEu), Freshwater Ecotoxicity (FWec), Marine Ecotoxicity (MEc), Terrestrial Ecotoxicity (TEc) and Fossil Resource Scarcity (FRS).

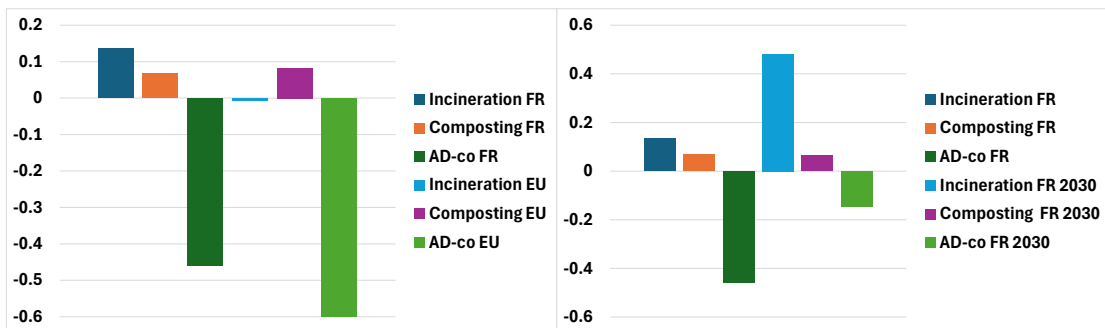


Figure 3. Environmental single score for different energy mix grids: a) France vs EU and b) France today vs 2030.

these compounds.

Regarding stratospheric ozone depletion (SOD) (kg CFC11-eq.), AD-co showed the least impact, with energy displacement creating environmental credits, while incineration's energy credits prove insufficient to offset continuous ozone-depleting compound production.

For terrestrial impacts, the analysis of acidification (TA) and ecotoxicity (TEc) (measured in kg SO₂-eq. and 1,4-DCB eq. emitted to industrial soil) reveals that composting demonstrates the highest impact, primarily due to fuel combustion during operations and energy production. Both AD-co and incineration benefit significantly from energy displacement credits, which effectively reduce their environmental impact in these categories.

Figure 2b present the comparison of the midpoint impact assessment of the three technologies with regards to the actual French energy mix grid and the 2030 horizon is shown. The reduction in high-carbon fossil fuel based technologies share from 60 % to 42 % drastically reduce the environmental credits of the three waste treatment technologies, revealing significant shifts in technology performance with the projected changes in energy mix composition. For fossil resource scarcity (FRS), the impact order changed, now Ad-co is the least impacting technology, followed by Incineration. The same results are found for freshwater ecotoxicity (FWEc), eutrophication (FWEu) and marine ecotoxicity (MEc). AD-co is the least impacting technology bringing credits; while composting and incineration result in higher environmental impacts. A slight reduction of -4 % to -14 % in the impact category of freshwater ecotoxicity is observed, primarily due to the increased share of energy co-generation using biogas. However, freshwater eutrophication and marine ecotoxicity show significant increases for incineration (130 % and 10.6 % respectively) and AD-co (70 % and 21 % respectively), linked to reduced energy displacement credits.

The global warming (GW) analysis for 2030 demonstrated perhaps the most dramatic shift, with a 108 % to 122 % relative increase for incineration and AD-co respectively. This shift transforms incineration from saving 16 million tonnes CO₂eq. to producing 1.38 million tonnes CO₂eq. annually, while AD-co shifts from saving 13.5 million tonnes CO₂eq. to producing 3 million tonnes CO₂eq.

Despite these increases, the analysis of human toxicity impacts shows that AD-co maintains its environmental advantage, even after experiencing a 46 % increase in human carcinogenic (HCT) and 7 % increase in non-carcinogenic toxicity (HNCT) impacts. Incineration follows a similar trend but to a lesser extent, with 37 % and 2 % increases respectively.

Fig. 3 presents the aggregated end-point environmental single score, they have been produced following ReCiPe 2016 [6] methodology. The analysis highlights how energy mix differences lead to varying technological

preferences. In the EU context, with its higher fossil fuel dependency, AD-co emerges as the least impacting technology available, followed by incineration and lastly composting.

However, the French context, with its less carbon-based energy mix, shows a different trend: AD-co remains the preferred option, but composting becomes more favourable than incineration due to reduced energy displacement credits. This trend becomes even more pronounced in the 2030 scenario, where AD-co maintains its position as the least environmentally impacting system despite losing a significant share of positive impact. Composting emerges as a valuable alternative with relatively small environmental impact, and incineration becomes one order of magnitude more impacting than composting and two orders more impacting than AD-co.

CONCLUSIONS

This study provides valuable insights into waste treatment technologies through two perspectives. In the context of Paris, the life cycle assessment demonstrated that anaerobic digestion with composting (AD-co) emerges as the most environmentally favourable option, followed by composting, with incineration showing the highest environmental impact. This hierarchy is maintained when the share of high-carbon sources in the energy mix is reduced. However, the decarbonisation of the mix increases the final impact of incineration and progressively reduces the interest of anaerobic digestion with composting.

The analysis of environmental impacts in different energy mix scenarios revealed a critical insight: the perceived advantages of WtE plants are largely artificial, created by avoided impacts in carbon-intensive energy contexts. As energy grids transition toward low-carbon renewable sources, this artificial benefit will decrease, highlighting the urgent need to shift toward alternative treatment systems like AD-co and composting. This relationship between waste treatment technologies and energy resources demonstrate how the environmental performance of waste management systems is intrinsically linked to the energy mix grid.

The specific impact assessment shows that AD-co consistently maintains its environmental advantage across different scenarios, while incineration's performance significantly deteriorates in lower-carbon energy contexts. For instance, in the 2030 scenario, AD-co remains the most environmentally sound option, despite reduced benefits from energy displacement, while incineration becomes notably less favourable, showing impacts two orders of magnitude higher than AD-co.

Based on these findings, some recommendations to the policymakers can be formulated: consider the projected changes in energy mix when planning long-term

waste management infrastructure, prioritize the development of AD-co facilities due to their consistent environmental benefits across different energy scenarios, and gradually transition away from incineration in regions with increasingly renewable energy mixes. Additionally, policymakers should consider incorporating composting facilities in their plans as complementary infrastructure to AD-co, particularly in areas with limited space or resources for AD-co implementation. Future studies should also consider technological advancements and various system configurations to provide a more comprehensive understanding of treatment options.

While these findings provide crucial environmental insights, it's important to recognize that a comprehensive assessment of waste processing systems must also incorporate economic and social dimensions to develop truly sustainable and practical solutions.

DIGITAL SUPPLEMENTARY MATERIAL

In the supplementary material, all the inventories and calculations can be found.

<https://psecommunity.org/LAPSE:2025.0013>

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