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Impact pathways: geo-operations for turning plastic waste into carbon capture

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Abstract

Purpose – We explore how an operations and supply chain approach to geo-engineering can enhance circular economy approaches and mitigate climate change. We illustrate how such geo-operations – specifically the combination of plastics and biowaste processing – can be systematically leveraged for carbon capture.

Design/methodology/approach – The study applies production theory and operations management perspectives to develop a carbon transfer model. It traces carbon flows through the extended plastics supply chain and interconnected natural systems, from raw material inputs, through production and reuse cycles, to the ultimate disposal. By mapping carbon transfers between natural systems and artificial systems, the framework highlights the systemic impact pathways for operations and supply chain management.

Findings – Single interventions such as bio-based materials, chemical recycling or policy instruments have limited impact in isolation. However, when combined systemically, these individual solutions can form geo-engineering operational pathways that draw out atmospheric carbon and refossilize it, thus transforming the plastics technosphere from a source of emissions to a means for carbon capture.

Research limitations/implications – The study is conceptual and develops theoretical propositions on systemic impact, rather than presenting empirical findings. Future research should empirically investigate the feasibility, scale and trade-offs of the proposed geo-operations pathways.

Practical implications – The carbon transfer model and impact pathways guide policymakers, producers and waste managers on integrating the circular economy and geo-operations for climate change mitigation and carbon capture.

Social implications – By reframing plastics not only as a source of problematic waste but also as a possible vehicle for climate mitigation, the paper suggests new opportunities and responsibilities for industry and society.

Originality/value – This paper proposes the development of geo-operations as a systemic pathway for integrating circular economy and carbon sequestration interventions. It also presents a framework to assess the impact of combinations of interventions on carbon flows.

Keywords Plastics technosphere, Circular economy, Carbon capture, Geo-operations

Paper type Impact pathways

1. Introduction

Plastics, which are often portrayed as part of the problem when tackling climate change, could become part of the solution (Stegmann *et al.*, 2022). For this possibility, researchers in the field

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of production, operations and supply chain management need to reach beyond the circular economy and actively start exploring how operational interventions in the technosphere (Hidiroglu *et al*., 2024) – all the human-made materials and structures, including our technology, machines and infrastructure – can deliver climate change mitigating impacts in the natural spheres: atmosphere (air), hydrosphere (water), geosphere (ground) and biosphere (living things). Accordingly, we focus on the plastics technosphere (all human-made plastics) and how it can be modified to capture atmospheric carbon and restore it to the ground, refossilizing accumulated emissions (Dunsmore, 1992) [1]. We present impact pathways that leverage the plastics technosphere, in concert with the biosphere, as an untapped means for carbon sequestration.

As with any technological solution fulfilling human purposes, progress depends on finding effective combinations of pre-existing and new solution elements (Arthur, 2009). Plastics require carbon, as they are primarily composed of carbon polymers (i.e. long molecular chains). Currently, practically all this carbon originates from fossil-based feedstocks (Geyer *et al*., 2017; Karali *et al*., 2024), leading to problems such as increased atmospheric CO_2 (accelerating climate change), accumulation of waste (e.g. the Great Pacific Garbage Patch) and uncontrolled flow of microplastics into nature (with largely unknown effects). To mitigate these undesirable effects of plastics, manufacturing, recycling and disposal must be combined in new ways that, over time, enable and complement each other, opening impactful operational pathways.

Researchers in production and operations management have recognized the need to explore how to effectively combine solutions for impact, introducing the concept of impact pathways as a starting point (Caniato *et al*., 2023). Closed-loop supply chains are identified as a means to leverage reuse and extend material life (De Giovanni, 2022), with cross-industrial collaboration a critical enabler for increasingly circular practices (Ratsimandresy and Miemczyk, 2025). However, circularity alone has limited impact for climate change mitigation, challenging us as researchers to look for ways to push beyond incremental improvements to opportunities to harness whole operational systems for carbon capture (Matos *et al*., 2024). The question is not whether individual technological solutions can have an impact on sustainability, but rather which combinations are truly worth pursuing and under what conditions they deliver meaningful impacts. Reaching beyond the circular economy (cf. Meys *et al*., 2021), we can engage in geo-operations: a new type of geo-engineering enabled by combining solutions in production, logistics and operations.

This paper contributes to production and operations management by introducing a framework for evaluating carbon transfer flows in the plastics technosphere. It is illustrated through an example of geo-operations that captures and refossilizes biogenic carbon, thereby extending the scope of the circular economy of plastics toward systemic climate-change mitigation.

2. Research setting and methodological approach

The impact pathways were developed as part of a multidisciplinary research project initiated by the Strategic Research Council (SRC) at the Academy of Finland to support policies for sustainable development [2]. The research approach combines problematization (Alvesson and Sandberg, 2011) and engaged research (Sternberg *et al*., 2024), challenging established assumptions and theoretical positions in the field of circular economy and sustainable operations while seeking new ways to address the reframed problem. During 2019–2024, we conducted 79 interviews across the plastics value chain, involving informants from private, public and non-profit organizations. We analyzed the collected data abductively. In other words, we drew on the existing literature (Alvesson and Sandberg, 2011) to address a real-world problem (i.e. the current unsustainability of the plastics industry), while collaborating actively with external stakeholders to confirm and validate our insights (Sternberg *et al*., 2024).

The problem framing and solution proposal were developed by the authors of this paper, engaging with researchers from the fields of polymer chemistry, plastics recycling and life-cycle assessment as well as representatives from various supply chain companies and policymakers. The hypothesis at the start of the project was that increasing the use of bio-based oils and recycled materials in plastic production would improve the sustainability of the plastics industry. However, over the course of the project, the possible introduction of bio-based and recycled materials in plastics production revealed difficult-to-overcome obstacles (Siltaloppi and Jähi, 2021). Furthermore, a detailed life-cycle assessment of substituting fossil-based oils with bio-based oils indicated that the sustainability impact would be marginal (Äkräs *et al.*, 2022). These observations were further corroborated in several workshops among industry stakeholders.

The substantial implementation challenges and limited available impact for the initial solution hypothesis led us to re-examine our assumptions. These challenges prompted us to seek new “possible possibilities,” adopting a possible operations approach that focuses on which actions and solutions are possible or impossible over time (Pil *et al.*, 2024). One starting point of this research was the possible use of biochar as reinforcement in plastics (Baniasadi *et al.*, 2024). The other starting point was the common technological basis of pyrolysis, which serves as both a technology for producing biochar from biowaste and for chemical recycling of plastic waste (de Oliveira *et al.*, 2021).

Expanding the scope of our investigation from the plastics supply chain to the plastics technosphere and its interactions with the natural spheres, we developed a carbon transfer model. The carbon transfer model identifies possible impactful transfer flows between natural spheres and the plastics technosphere. We then proceeded to examine the current applications of pyrolysis based on the transfer flows of the carbon transfer model, iteratively leading to the development of an empirically grounded use case for copyrolysis of plastic waste and bio-waste for refossilization.

3. Carbon transfer model: input-transformation-output flows through the plastics technosphere

The plastics technosphere refers to the global, interconnected system through which plastic materials are produced, distributed, used and disposed of. It encompasses a vast network of technological infrastructures – such as petrochemical plants, manufacturing facilities, logistics systems and recycling centers – as well as the business ecosystems that drive it, including polymer producers, plastic converters, packaging companies, consumer goods manufacturers and waste management firms. Looking beyond circularity improvements (Matos *et al.*, 2024; Meys *et al.*, 2021), we examine the potential of geo-operations. How can manufacturing, logistics and waste handling operations be harnessed to systematically transfer carbon from the atmosphere through the biosphere and the plastics technosphere, ultimately storing it safely in the geosphere? The growing demand for plastic materials renders recycling and circularity insufficient, necessitating the exploration of additional ways to reduce and even reverse carbon emissions by utilizing the plastics technosphere as a means (Hidiroglu *et al.*, 2024; Stegmann *et al.*, 2022).

The currently dominant combination of solutions in the plastics industry transfers fossil carbon from the ground to the atmosphere, thereby accelerating climate change (see Figure 1). Building on production theory and operations management principles (Spearman and Hopp, 2021, p. 808), we highlight the control of carbon flow through the plastics technosphere. At the center is the circular economy of plastics, routing the input-output transfers between and within the natural spheres (atmosphere, biosphere, geosphere and hydrosphere).

The problem is that transfer flows through the plastics technosphere are highly unbalanced [3]. Climate change inhibiting transfer flows (shown as 1 → 2 → 3) captures carbon from the atmosphere and refossilizes it for long-term storage; for example, plastics or composites made from bio-based raw materials that are converted to biochar at the end of their life cycle. Current operations (shown as 4 → 2 → 5) take carbon from the soil and release it into the atmosphere.

The plastics technosphere uses carbon in the form of plastics for human purposes in different ways (single use, reuse and long-time use); produces plastics from virgin or recycled

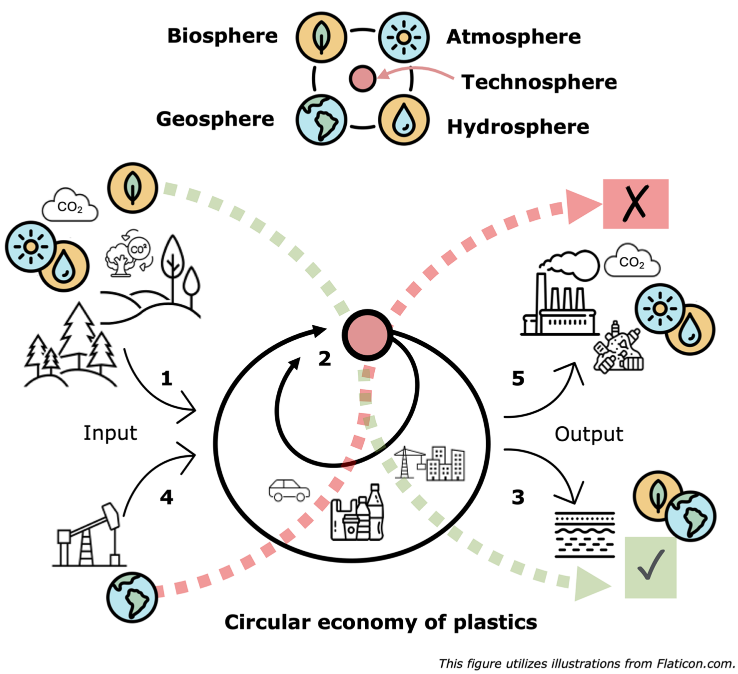

Figure 1. Carbon transfer model. Source: Authors' own work

materials (upcycling and downcycling), moving and storing carbon within and between the spheres (consumption, accumulation and disposal). The annual plastics production requires a significant input of carbon annually (0.3 GtC, gigatons of carbon) to feed the plastics technosphere [4]. Unless properly treated at the end of their life, plastics end up in landfills and can enter waterways or oceans, where they gradually break down into microplastics. If we choose to avoid these problems by incinerating the waste, plastics made from fossil raw materials accelerate climate change by releasing carbon dioxide into the atmosphere, even if used as fuel for energy production (Dokl *et al.*, 2024). In contrast, bio-based plastics and biocomposites transfer carbon from the atmosphere to plastic products (de Oliveira *et al.*, 2021) [5]. Single-use plastics generate demand for more disposable plastics, whereas long-term use, reuse and recycling of plastics slow down the demand for new inputs of fossil carbon (Reike *et al.*, 2018). Replacing incineration with recycling and refossilization delays and prevents the release of bound carbon to the atmosphere (Qureshi *et al.*, 2020).

There are many different ways to reuse plastics in the technosphere to prevent the transfer of carbon from the technosphere to the natural spheres, specifically the 2 → 5 and 2 → 3 transfer flows in the carbon transfer model. Increasing the number of cycles within the technosphere (circular transfer flow 2 → 2) reduces the need for new carbon inputs and postpones the output to natural spheres. The most promising mainstream approach is chemical recycling, which utilizes plastic waste to produce the oil and gas inputs necessary for manufacturing new plastic (Economist, 2025). A much more straightforward, yet scalable solution for settings that lack infrastructure for collecting plastic waste for mechanical and chemical recycling is the so-called "ecobrick." The principle is that people fill plastic bottles with miscellaneous plastic waste and then use the resulting compacted ecobricks as building materials for simple and safe carbon sequestration (Ecobricks, 2025). Other, more complex solution examples for prolonging the circular transfer flow focus on upcycling the plastic material into more valuable components. For instance, processing plastic waste with microwaves can upcycle it into clean hydrogen and carbon nanotubes, which have a wide range of high-tech applications (National Energy Technology Laboratory, 2024).

Some of the innovative solutions currently in development could also be used to transfer carbon from the atmosphere to the technosphere, reversing the emissions flow to sequester carbon (5 → 2 in the carbon transfer model). One example of this possibility becoming feasible is the chemical upcycling of polyethylene terephthalate (PET) to a CO_2 binding material (Poderyte *et al.*, 2025). L'Oréal, in collaboration with Total and technology developer Lanza Tech, has a circular economy solution that prevents carbon from entering the atmosphere (Total, 2020). The solution captures industrial carbon emissions before they are released into the atmosphere, converts the carbon dioxide into ethanol, and then uses it as a raw material for plastics in packaging for L'Oréal cosmetics products. With access to clean energy, such as solar or wind-generated electricity, the solution can potentially be used not only to capture emissions but also to sequester carbon from the atmosphere.

4. Example of possible geo-operations: refossilization of plastics with biomass

The carbon transfer model highlights the potential of geo-operations in transforming the plastics technosphere into a carbon sink. The opportunity arises at the end of the plastic's life cycle, where the goal is to refossilize carbon in a form that can be safely and permanently buried in the soil. Properly done, the transfer flow 2 → 3, which stores carbon from the plastic technosphere in the geosphere, also addresses the microplastic problems caused by the insufficient handling of plastic waste. This way, the plastic technosphere can become part of the solution for combating climate change as well as addressing the microplastics problem of its own creation.

However, instead of refossilization, technology developers have focused on chemical recycling and the production of oils and gas from plastic waste (e.g. Economist, 2025) or upcycling (National Energy Technology Laboratory, 2024). While transforming plastic waste to char utilizes the same basic technology – pyrolysis – as chemical recycling, the specific design of the equipment differs (Al-Rumaihi *et al.*, 2022). The technical requirements for plastic-char production are lower than those for chemical recycling and the equipment design can be simpler and less costly, resembling that for bio-char production from biological waste materials (Amrullah *et al.*, 2022; Hasan *et al.*, 2025).

Operationally, the combination of plastic and bio-based feedstocks in copyrolysis for the purpose of refossilization is an opportunity to leverage the plastics technosphere for carbon capture. Addressing the challenge of dirty plastic waste in agriculture, construction and grocery retailing, mixing plastics and biomaterials for char production is a viable alternative approach, with the potential for a significant impact (see Table 1).

In copyrolysis with biomass, plastic waste can enhance the structural stability of the resulting char, facilitating long-term carbon storage and refossilization. The impact of mixed feedstock input is more char, less external energy needed, more extensive carbon capture, and

Table 1. Alternative solutions

	Feedstock input		
	Plastics only	Biomass only	Plastics + biomass, alternatively biocomposites
Char yield	Low (~5 to 10%) [6]	Medium (~20 to 40%) [6]	High (~25 to 50%) [7]
Energy input	Low (after startup) [6]	Medium (needs drying) [8]	Low (plastics help dry biomass) [9]
Carbon capture potential	Medium [6]	Medium–High [10]	High [11]

Source(s): Authors' estimate based on literature, key sources indicated with footnotes effective refossilization of mixed waste streams (Adeniyi *et al.*, 2024; Amrullah *et al.*, 2022; Hasan *et al.*, 2025). While the optimal process parameters depend on the material inputs and the desired outputs on a case-by-case basis, copyrolysis increases the overall efficiency (Al-Rumaihi *et al.*, 2022; Cheng *et al.*, 2024; Hasan *et al.*, 2025; Wang *et al.*, 2022). This combined approach has a high potential impact on the refossilization of waste in agriculture, construction and grocery supply chains.

Scaling up the copyrolysis use case scenario to include all plastics produced, the refossilization of plastics with biowaste could, over time, remove the accumulated carbon emissions from the atmosphere and sequester them in the geosphere, while avoiding plastic waste and microplastics. Figure 2 illustrates how plastics can be operationally leveraged for carbon capture in copyrolysis with biomass. In the scenario where all plastics manufactured would eventually be refossilized, the global annual fossil carbon emissions from the whole technosphere to the atmosphere (9.7 GtC, gigatons of carbon) [12] could be recaptured in 23 years. This is assuming that the annual plastics manufacture (0.3 GtC) is copyrolyzed in a 1 to 3 ratio with biomass at the maximum 50% yield, capturing 0.6 GtC annually. The energy source for the carbon capture is the copyrolysis process itself. The gases produced by the process are used to heat and power the process, generating approximately 15% carbon emissions or 0.18 GtC. To sum up, 23 years of geo-operations capturing 0.42 GtC annually equals 9.7 GtC, corresponding to the current annual emissions of all fossil fuel use, not just the plastics subsphere.

The systemic impact of the suggested copyrolysis is that it transforms plastic waste into a resource for carbon sequestration. After refossilization, the plastics are not just waste to be managed but a means for carbon storage. The carbon transfer model illustrates an impact pathway for geo-operations that mitigate the climate effects of the plastics technosphere by extending it consciously into the biosphere. Biowaste contains carbon drawn from the atmosphere by the biosphere and copyrolysis with plastic waste interrupts the biogenic (natural) carbon cycle [13], reducing the emissions of greenhouse gases from biowaste incineration or natural decomposition, instead storing it in the ground.

The implication of the outlined geo-operations example is that the plastics technosphere is harnessed along with the biosphere to mitigate atmospheric CO_2 levels. Recent studies argue that this area remains insufficiently examined (Adeniyi *et al.*, 2024; Cheng *et al.*, 2024), including impact assessment on the biogenic carbon cycle (van Schoor *et al.*, 2025).

5. Discussion: facilitating geo-operations aligned with the carbon transfer model

Systemically impactful geo-operations – illustrated by the carbon-transfer model in Figure 1 – require enabling the transfer flows 1 → 2, 2 → 2 and 2 → 3, while counteracting flows such

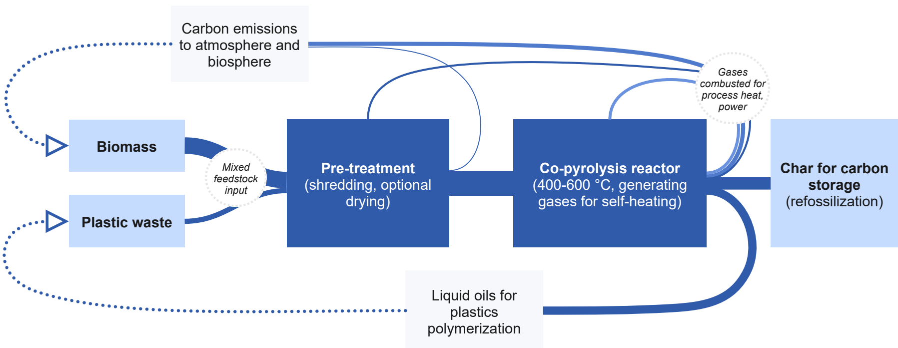

Figure 2. Refossilization of plastics with biomass (including biocomposites). Source: Authors' own work

as 4 → 2 and 2 → 5. As the refossilization example demonstrates, interventions in the technosphere can purposefully redirect biogenic carbon flows from the atmosphere back into the geosphere. Advancing such impactful transfer flows calls for research in three critical areas. The first examines incentives, regulation and financing mechanisms to create viable conditions for carbon capture geo-operations. The second concerns the identification and integration of available solutions that operationally control and capture carbon flows across system spheres. The third seeks to extend LCA impact evaluations beyond products or processing stages toward systemic assessment, enabling a deeper understanding of how to achieve long-term and large-scale carbon transfers.

Pathway 1: For the first area, the critical questions are how much society is willing to pay for carbon capture and how such resources should be collected and redistributed. Building on insights into the role of regulation in shaping sustainable operations (De Giovanni, 2022), new research is needed on how financial models and geo-operations can be combined. For instance, incentives for refossilization could be funded by linking them to a tax on fossil carbon entering the plastics technosphere. A carbon-added tax, levied alongside value-added tax (VAT), could simultaneously counteract the flow 4 → 2 and generate revenues to support refossilization (transfer flow 2 → 3 in the carbon transfer model in Figure 1). To understand how we can support the expansion of carbon capture infrastructure, we encourage operations and supply chain management scholars to investigate: How can mechanisms such as carbon-added tax be integrated into supply chains to facilitate carbon capture investments and geo-operations initiatives? What are the financial mechanisms and governance structures available to incentivize geo-operations across the supply chains? How can financial models be created and implemented that combine carbon taxation on fossil inputs with subsidies for carbon capture and utilization processes?

Pathway 2: In the second area, research should explore innovative combinations of operational solutions that make systemic carbon capture feasible. The literature on closed-loop supply chains (De Giovanni, 2022) and cross-industrial collaboration (Ratsimandresy and Miemczyk, 2025) highlights the importance of connecting multiple actors and processes. For example, realizing the refossilization transfer flow requires identifying which specific combinations of recycling technologies, plastic and biowaste sourcing and logistics arrangements can cost-effectively capture carbon at scale. This calls for empirical and modeling studies across sectors such as agriculture, forestry, retail and construction. Key research questions include the appropriate scale (“right size”) and location (“right place”) of geo-operations facilities. For copyrolysis, scale and location decisions affect transport and handling requirements for both waste inputs and refossilized carbon outputs. Small, distributed facilities may minimize logistics needs, while larger, centralized facilities improve equipment utilization but raise transport costs. These trade-offs demand further study in light of existing infrastructure and investment constraints. Therefore, we suggest research focusing on, for example: How does operations management decisions (facility location, transportation networks and storage site proximity) shape the economic viability and carbon capture potential of plastic waste refossilization? How can geo-operations be designed and optimized to minimize the total system costs while maximizing the carbon capture (e.g. to find the ideal logistics network configurations for sorting, routing, collection, storage, etc.)?

Pathway 3: The third research area concerns the challenge of assessing interventions in open systems. Conventional life cycle assessment (LCA) methods are product- and process-specific, often producing useful metrics but overlooking scalability and long-term dynamics. As Matos (2024) cautions, incremental improvements may appear beneficial in isolation but fail to deliver transformative outcomes over time. For example, Ecobricks may seem efficient but lack scalability, whereas copyrolysis is less energy efficient but more scalable and enduring. Research is therefore needed on open-system approaches that capture systemic carbon transfers, scalability and continuity, better reflecting the insights of the carbon-transfer model. To address such needs, we call for research on the requirements for extending LCA system boundaries to capture open-system carbon transfers and biogenic loops in circular supply chains. Potential questions on this pathway are: How can the LCA methodologies be revised or expanded to better account for dynamic changes and temporal variations in measuring carbon transfers at the system level? How could system dynamics modeling be integrated with LCA to support adaptive management of carbon capture interventions under uncertainty and systemic change?

While clearly distinct, these pathways are interconnected. For instance, the implementation of financial and regulatory interventions (the first research area) likely necessitates innovations in operational solutions (the second). A carbon-added component to VAT could require combining regulation (Dehio *et al.*, 2023) with digital product passport systems (Tabata and Tsai, 2025). The digital passport could identify products using recycled or bio-based materials, exempting them from a carbon-added tax, while products lacking such credentials would be taxed.

To conclude, transforming the plastic technosphere from a source of pollution to a resource for improving sustainability is challenging. It is not only about innovating novel solutions and operational improvements but also about enabling and incentivizing the necessary impact pathways. Yet, if the necessary combination of solutions is identified and implemented, it enables impactful new geo-operations for carbon capture and storage.

Notes

1. With "refossilization" we refer to "returning carbon to its fossil state." In the process, used fossil carbon-based materials (such as plastic waste) and biowaste can be transformed into stable carbon compounds and permanently stored. Instead of letting these materials pollute the environment or release carbon into the atmosphere uncontrollably, refossilization locks the carbon away for geological timescales, similar to how nature originally stored it as oil and gas deposits millions of years ago.

2. See https://valuebiomat.fi and https://www.aka.fi/en/strategic-research/strategic-research/strategic-research-in-a-nutshell/programmes-and-projects/completed-programmes/impres/

3. The total carbon transfers through the technosphere (including the plastics sub-technosphere) are roughly 10 GtC (gigatons of carbon) annually (Dokl *et al.*, 2024; Friedlingstein *et al.*, 2025; Geyer *et al.*, 2017), of which about 9% (0.9 GtC) accumulates in durable materials such as plastics, concrete and asphalt each year (Hidiroglu *et al.*, 2024). These flows are dwarfed by the large but balanced natural exchanges among Earth's other spheres. Photosynthesis and respiration exchange approximately 110 GtC between the atmosphere and biosphere, while ocean–atmosphere exchanges are roughly 55 GtC in each direction (IPCC, 2023). Carbon burial (natural fossilization) from the biosphere to the geosphere adds about 0.2 GtC, balanced by volcanic and weathering outgassing of around 0.1 GtC (IPCC, 2023). With the carbon transfer flows 4 → 2 → 5 dominating over 1 → 2 → 3, the technosphere currently injects about 10 GtC from the geosphere into the atmosphere each year (IPCC, 2023; Friedlingstein *et al.*, 2025). The plastics technosphere accounts for roughly 5% of these technospheric emissions (Dokl *et al.*, 2024; Karali *et al.*, 2024).

4. The global production of plastics increases rapidly and has already resulted in an inflow of 0.3 GtC to the plastics technosphere annually (Dokl *et al.*, 2024), whereas approximately 0.1 GtC is retained in prolonged or repeated use (Geyer *et al.*, 2017). Over time, this accumulation has created a carbon stock of about 2.9 GtC in the plastics technosphere, based on the projected plastics use, waste and stock (Dokl *et al.*, 2024; Geyer *et al.*, 2017; Stegmann *et al.*, 2022) and an estimated 75% average carbon content in plastics products (authors' own estimate). Since the plastic use grows fastest in regions with limited recycling infrastructure, it is likely that over half of the plastics will continue to be landfilled by 2050 (Dokl *et al.*, 2024).

5. Biocomposites are produced by blending bio-based substances directly with (fossil) plastic raw material, thereby increasing the ratio of renewable resources in the material. Examples of such bio-based fillers are natural fibers from industrial side-streams or agricultural residuals that have no food use.

6. Al-Rumaihi *et al*. (2022), Wang *et al*. (2022).
7. Adeniyi *et al*. (2024), Al-Rumaihi *et al*. (2022).
8. Al-Rumaihi *et al*. (2022).
9. Wang *et al*. (2022).
10. Al-Rumaihi *et al*. (2023), Matovic (2011).
11. Adeniyi *et al*. (2024), Al-Rumaihi *et al*. (2023), Matovic (2011).
12. Friedlingstein *et al*. (2025).
13. The biogenic cycle, which biowaste is a part of, is a significant source of greenhouse gases, such as carbon dioxide, methane and nitrous oxide; see, e.g. Yasmin *et al*. (2022).

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