Waste and Material Footprints in prospective LCA: a study of 1600+ activities from 2020-2050

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Abstract (400/400 words)

Purpose 75 words

Advancing a circular economy requires direct, system-wide quantification of the waste and material flows attributable to human activity. Yet Waste and Material Footprints (WMFs) remain under-reported in standard LCA and sparsely integrated into prospective assessments. We quantify WMFs across the ecoinvent database and examine their evolution under contrasting socio-economic pathways to: (i) reveal sectoral and supply-chain hotspots; (ii) position WMFs alongside conventional LCIA endpoints; and (iii) assess how scenario-aligned backgrounds modify footprint magnitudes and interpretation.

Methods 125 words

We constructed prospective LCI databases with *premise* (based on ecoinvent 3.9.1), aligned to two divergent *REMIND* Integrated Assessment Model (IAM) pathways—SSP1-PkBudg500 and SSP5-PkBudg500—for 2020–2050. We then applied *T-reX* to enable tracking of 50+ categories of waste and material flows and computed WMFs for >1,600 market activities. In parallel, we calculated ReCiPe 2016 endpoint indicators to benchmark WMFs against established damage metrics. Activities were grouped into sectors to identify hotspots and explore temporal and scenario contrasts. Because the underlying inventories use economic allocation, we explicitly discuss interpretive limits for mass-based inference in the context of allocation-driven effects.

Results and discussion 125 words

Sectorally, mining, metals, and chemicals dominate both total and hazardous waste footprints, mirroring patterns in ReCiPe endpoints and reinforcing WMFs' decision relevance for risk, circularity, and prevention strategies. WMFs show statistically meaningful correlations with human-health and ecosystem damage indicators at activity and sector aggregation. Across 2020–2050, we observe modest WMF reductions in both pathways, however, the magnitude of change is smaller than expected given policy narratives on waste prevention, improved collection/sorting, higher recycling yields and qualities, and expanded secondary-material markets. This gap likely reflects limited representation of waste-system transformations in IAM-linked pLCIs and highlights where circularity dynamics are under-specified. Interpretation of absolute WMF levels is also allocation-sensitive: price-based allocation can amplify high-value co-products and attenuate low-value by-products, decoupling WMFs from physical mass balances.

Conclusions and recommendations – 150 words

WMFs complement LCIA endpoints in prospective LCA by making material throughput and waste generation explicit, revealing hotspots that standard impact profiles can obscure. To approach mass-consistent interpretation, future work should test physical/flow-based allocation and explore consequential databases. Most critically, signigicant effort will need to be made to embed explicit waste-sector trajectories in prospective LCA databases in the way that sectors such as energy and transport are already included. Our results indicate a methodological gap: without scenario-dependent circularity modules, IAM-aligned databases understate WMF dynamics over time. Integrating these transformations will improve the fidelity and policy usefulness of pLCAs intended to guide circular-economy strategies.

Keywords

Circular economy, Waste footprints, Material footprints, Prospective life cycle assessment, Scenario-based life cycle modelling, Integrated assessment models, Critical raw materials, Integrated assessment models

List of abbreviations

CE	Circular Economy
CRM	Critical Raw Material
CPC	Cooperative Patent Classification
EF	Ecological Footprint
EoL	End-of-Life
IAM	Integrated Assessment Model
IMAGE	Integrated Model to Assess the Global Environment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MF	Material Footprint
MFA	Material Flow Analysis
pLCA	Prospective Life Cycle Assessment
REMIND	REgional Model of Investment and Development
RCP	Representative Concentration Pathway
ReCiPe	A standard LCIA method set
re-X	A broad set of circular economy strategies (“reduce”, “reuse”, “repair”, “recycle” etc.)
SDG	Sustainable Development Goal
SSP	Shared Socioeconomic Pathway
T-reX	The Tool for analysing re-X in LCA
UNFC	United Nations Framework Classification for Resources
WF	Waste Footprint
WMF	Waste and Material Footprint

1 Introduction (~1200 words)

Environmental context: why circularity and waste matter

Human activities continue to exceed key planetary boundaries, intensifying climate change, biodiversity loss, and resource depletion. In response, the transition to a circular economy has become a central pillar of sustainability policy (Ellen MacArthur Foundation, 2015; European Commission, 2020; Pardo & Schweitzer, 2018). Circular strategies seek to decouple well-being from primary material extraction by reducing material demand and preventing waste across value chains through 're-X' measures—refuse, rethink, repair, remanufacturing, and recycling (Kirchherr et al., 2017; Reike et al., 2018). Recent geopolitical tensions further underscore the vulnerability of globalised supply chains and the need for material efficiency and system resilience (Carrara et al., 2023; Hartley et al., 2024).

Waste and material footprints in LCA

Footprints provide compact indicators of environmental pressure. The Ecological and Carbon Footprints initiated this "footprint family" (Čuček et al., 2015; Wackernagel, 1994), which has since expanded without fully converging on a coherent framework (Giampietro & Saltelli, 2014; B. G. Ridoutt & Pfister, 2013; Vanham et al., 2019). The Material Footprint (MF)—the total supply-chain material use attributable to products, sectors, or economies—correlates strongly with human-health and biodiversity damage and is recognised by the United Nations for SDG monitoring (Lenzen et al., 2021; Wiedmann et al., 2013). By contrast, the Waste Footprint (WF)—the mass or volume of waste generated along value chains, including hazardous fractions—remains less developed and is often overlooked, despite evidence linking waste burdens to environmental damage and social inequity (Akese & Little, 2018; Laurenti et al., 2023; Steinmann et al., 2017). Considering WF alongside MF highlights where material use translates into waste generation, where hazardous waste arises, and where interventions may yield the greatest returns for circularity.

Life Cycle Assessment (LCA) is the prevailing method to quantify environmental impacts across product and service life cycles (Guinée et al., 2010). In standard practice, life cycle impact assessment (LCIA) methods (e.g., ReCiPe, CML) convert inventory flows—elementary exchanges between technosphere and biosphere—into impact scores (Guinée et al., 2002; Huijbregts et al., 2016). Several LCIA frameworks incorporate aspects of waste and material use (e.g., Swiss Eco-Factors, EDIP, EN15804, Crustal Scarcity Indicator) (Arvidsson et al., 2020; CEN (European Committee for Standardization), 2019; Hauschild & Potting, 2004; Swiss Federal Office for the Environment (FOEN), 2021), yet few provide transparent, mass-consistent accounting of MF and WF. Some also rely on abstract units (e.g., Umweltbelastungspünkte in the Swiss Eco-Factors) that can complicate interpretation. Moreover, because waste is commonly modelled as a service (treatment), the magnitude and distribution of waste generation along supply chains can remain obscured, making upstream waste effectively "invisible" (Beylot et al., 2018; Guinée & Heijungs, 2021).

In practice, waste is often defined as material with negative economic value, but its significance extends far beyond treatment emissions (Bisinella et al., 2024; Guinée et al., 2004; Laurenti et al., 2023). Empirical studies confirm associations between waste burdens, environmental damage, and disproportionate impacts on vulnerable communities (Akese & Little, 2018; Pellow, 2023; B. Ridoutt et al., 2010). Reporting WF and MF alongside conventional LCIA indicators can therefore make material throughput and waste generation explicit, reveal hidden hotspots, and improve prioritisation of circular economy strategies.

Future-oriented LCA and prospective background databases

Emerging technologies required for deep decarbonisation will scale over coming decades, often after substantial learning and capital investment (International Energy Agency (IEA), 2021, 2022). Prospective LCA (pLCA)—also called ex-ante or anticipatory LCA—assesses likely environmental implications early enough to inform design and policy (Cucurachi et al., 2018; Van Der Giesen et al., 2020). Robust pLCAs require background data that reflect plausible future economic, technological, and policy conditions. Prospective life cycle inventory (pLCI) databases therefore combine current LCI data (e.g., ecoinvent) with scenario information from integrated assessment models (IAMs) and other sources (Sacchi et al., 2022; Steubing et al., 2023).

IAM scenario frameworks typically pair a shared socio-economic pathway (SSP)—a narrative of societal development from sustainability-oriented (SSP1) to fossil-intensive (SSP5)—with a representative concentration pathway (RCP) that specifies a climate outcome via radiative forcing, corresponding to temperature goals such as 1.5–2 °C (Aboumahboub et al., 2020; Meinshausen et al., 2020; Stehfest et al., 2014; Van Vuuren et al., 2017). Implemented in IAMs, SSP×RCP pairings generate region- and sector-specific trajectories for technology deployment and emissions (Sacchi et al., 2022). These scenarios are bounded by resource availability, infrastructure lock-in, and policy constraints such as carbon pricing, which shape feasible transitions (Pauliuk et al., 2017).

premise, REMIND, and sectoral transformations

The premise workflow connects IAM projections to ecoinvent, producing pLCIs that regionalise markets and update process and supply-chain parameters for selected sectors (Sacchi et al., 2022; Sacchi et al., 2023). The most widely used IAMs are the REgional Model of Investment and Development (REMIND) (Aboumahboub et al., 2020) and the Integrated Model to Assess the Global Environment (IMAGE) (Stehfest et al., 2014). Neither IAM scenarios nor LCI databases currently provide full, high-resolution coverage across all sectors and regions. IAMs are detailed for electricity but sparser for agriculture, chemicals, and material cycles; standard LCIs prioritise current technologies, leaving emerging options under-represented (Pauliuk et al., 2017; Sacchi et al., 2023). The current default transformation domains include electricity generation and markets (with storage), cement (clinker ratio, kiln efficiency, optional CCS), iron and steel (process efficiency and CCS), fuels (refining, synthetic and biofuels, hydrogen), road freight (powertrain shares and fleet relinking), batteries (mass/energy-density scaling and market composition), heat supply (CO_2 factors), air-pollutant factors, and biomass markets distinguishing purpose-grown from residual feedstocks (Sacchi et al., 2023). Additional research has produced additional scenarios that can be integrated into pLCA databases with premise for sectors such as cobalt (Van Der Meide et al., 2022), hydrogen (Wei et al., 2024) and cement (Müller et al., 2024).

While the aforementioned sectoral transformations can result in indirect changes to future waste flows

(McDowall et al., 2025), waste management is not yet a dedicated transformation domain and other waste-sector inventories remain largely as they appear in the base database (Bisinella et al., 2024).

Aim and contribution of this study

Prospective analyses in LCA rely on the completeness and consistency of pLCIs, though, currently, they insufficiently represent waste-sector dynamics, creating a ‘waste gap’ that limits interpretation of future scenarios. Addressing this gap requires first clarifying how waste and material flows are represented in existing LCA and pLCA databases at both macro and activity levels.

This study applies a purpose built python tool T-reX (McDowall et al., 2025)—integrated within Brightway and compatible with premise-based pLCIs—to explore and quantify waste generation (including hazardous waste) and material consumption (especially CRMs) across activities and sectors. Our objectives are to: (i) compute waste and material footprints at multiple levels of aggregation, (ii) identify hotspots along supply chains under present and prospective background conditions, and (iii) illustrate how results support circular-economy strategies and supply-chain risk management.

Rather than developing a new LCIA method or prospective database, we demonstrate how targeted footprint accounting complements existing indicators. By reporting total waste, hazardous waste, and material consumption, and highlighting sectoral hotspots, our analysis shows how footprint accounting makes hidden burdens visible, clarifies interpretive limits, and delivers actionable insights for circular-economy policies and resource-risk management. Importantly, this work also provides a step toward embedding explicit waste-sector dynamics in future pLCA databases, where dedicated transformation modules could capture prevention, recycling, and secondary-material pathways alongside energy and transport transitions.

2 Methodology (1500 words)

2.1 Selection and creation of pLCA databases

Using the LCI database *ecoinvent* (version 3.9.1) (Wernet et al., 2016) as a basis, we constructed pLCI databases using *premise* (Sacchi et al., 2022) over ten-year intervals from 2020 to 2050. *premise* links IAM outputs to background LCI data by regionalising markets and updating technology efficiencies, fuel mixes, and emissions profiles; in our case, REMIND outputs drove these updates. REMIND is a global energy–economy–climate model that produces internally consistent projections of energy demand, technology portfolios, and greenhouse-gas emissions under alternative socio-economic narratives (Aboumahboub et al., 2020). We selected two contrasting REMIND pathways: SSP1-PkBudg500 and SSP5-PkBudg500. SSP1 ("sustainability") represents low challenges to mitigation, rapid diffusion of clean technologies, and lower energy and material intensities. SSP5 ("fossil-fuelled development") represents high economic growth coupled with high energy demand and a strong reliance on fossil fuels, thereby raising mitigation challenges (Bauer et al., 2017; Kriegler et al., 2017; Van Vuuren et al., 2017).

Within the SSP–RCP framework, the "PkBudg500" constraint imposes a stringent cumulative CO_2 budget consistent with 1.5 °C-class mitigation (often associated with RCP1.9 in the literature), which forces both worlds to meet a comparable climate target (Van Vuuren et al., 2011). We deliberately use the same PkBudg500 constraint for SSP1 and SSP5 to enhance interpretability of pLCI comparisons. Using the same carbon budget (PkBudg500) for SSP1 and SSP5 holds climate ambition constant, so differences in the resulting pLCIs reflect socio-economic and technological structure rather than target stringency. This improves attribution: contrasts in waste and material footprints stem from patterns of demand, fuel mixes, and infrastructure, not from divergent radiative-forcing goals. An approximately 500 Gt CO_2 century-scale budget is a 1.5 °C–class constraint (often associated with RCP1.9), ensuring major energy transitions with material implications (electrification, CCS, hydrogen, storage) appear in both pathways, though to different extents. Thus, SSP1-PkBudg500 and SSP5-PkBudg500 share a common climate constraint but diverge structurally, providing a controlled basis for comparing footprints in prospective LCA (Sacchi et al., 2022; IPCC, 2018).

2.2 Waste and material footprinting with T-reX

T-reX is a computational workflow that derives waste and material inventory footprints directly from life cycle inventories and makes them calculable like standard LCIA indicators. It screens the technosphere to detect exchanges representing wastes and to infer purchases of material markets as proxies for supply-chain material demand, groups matches into user-defined categories, and builds pseudo-LCIA methods that aggregate the targeted exchanges. Footprints can be computed for activities, sectors, or whole databases under current or scenario-aligned backgrounds (Mutel, 2017; Sacchi et al., 2022).

For each category, T-reX mirrors selected technosphere exchanges into an auxiliary "pseudo-biosphere" and assigns characterisation factors to these mirrored flows, preserving Brightway calculation mechanics while yielding inventory totals rather than impact-characterised scores (Wernet et al., 2016; Guinée et al., 2004). Waste is identified via exchange names and treatment-chain metadata, surfacing "hidden" wastes otherwise absorbed by downstream treatment. Material demand is inferred from purchases of the corresponding market activities and can be aggregated across regions or combined into composite indicators (e.g., rare earth elements). The same logic applies to prospective databases aligned to IAM trajectories via premise (Sacchi et al., 2022).

Outputs are mass/volume totals of targeted technosphere exchanges, supporting interpretation and hotspotting alongside conventional LCIA endpoints. Because indicators are inventory-based, results reflect system models and allocation; co-production can yield net negative demands where one product's supply offsets purchases elsewhere. In prospective analyses, T-reX reveals where scenario-dependent background changes alter waste and material footprints and where such dynamics remain under-specified, indicating priorities for embedding explicit waste-system modules in pLCI databases. In sum, T-reX adds a transparent layer of footprint accounting that complements LCIA by quantifying material throughput and waste generation and enabling consistent comparisons across activities, sectors, scenarios, and time (Mutel, 2017; Wernet et al., 2016; Guinée et al., 2004; Sacchi et al., 2022).

2.3 Selection of activities in the LCA/pLCA databases

We restricted the analysis to a transparent, comparable set of background "market" activities from each LCI database (baseline ecoinvent and its prospective variants), then harmonised, classified, and merged them. First, all activities were exported to a tabular structure and column names aligned (e.g., normalising type → activity type). We then parsed the ISIC and CPC classifications embedded in ecoinvent metadata, padding code strings and casting them to integers; missing values were assigned sentinel codes. This enabled uniform filtering and later grouping.

Filters were applied to isolate the activities of interest. By default, we selected only activities whose names begin with "market for …" and whose activity type equals "market activity", thereby focusing on market supply nodes rather than transformation or site-specific producer datasets. To ensure global comparability, we further restricted locations to ecoinvent's global aggregates (GLO, RoW, World). We excluded activities that are waste or service oriented (name, CPC, or ISIC containing "recovery", "treatment", "disposal", "waste", "services", "scrap", "site preparation", "construction", "maintenance") to avoid conflating technosphere waste management with product supply. Finally, we limited reference units to mass and volume commodities (kilogram, cubic meter) so that material and waste footprints could be interpreted consistently across the activity set.

After filtering per database, we assigned broad product categories and sub-categories from CPC ranges (e.g., ores/minerals & fuels, basic metals & alloys, plastics & rubber, pulp & paper), creating a consistent sectoral mapping for hotspot analysis.

For projects using multiple databases (e.g., present-day vs. premise-derived prospective backgrounds), filtered activity lists were concatenated and harmonised. We forward–backfilled missing classifications within name groups, and re-applied the activity type criterion to remove non-market remnants. Outputs were written to per-database CSVs and to a merged master file for subsequent footprint computation and sectoral aggregation.

This approach intentionally prioritises (i) market-level representativeness over plant-level specificity; (ii) globally comparable inventories over regional differentiation; and (iii) physically interpretable commodities over service or energy-only flows. Limitations include potential omission of region-specific markets, energy carriers with non-mass units (e.g., kWh), and any product supplied exclusively via non-market datasets. We note that name-based grouping can collide where names are reused across contexts; unique identifiers (activity code + database) mitigate this risk in downstream steps. Sensitivity tests (reported elsewhere) explore the effect of relaxing the location, unit, and activity-type constraints.

2.4 Categorisation of activities

To enable robust benchmarking—across sectors, and within sectors and sub-sectors—we grouped activities using the Central Product Classification (CPC) codes stored in the ecoinvent metadata. CPC is the United Nations' product taxonomy that organises goods and services by their material/functional characteristics; in LCA databases it provides a stable, method-agnostic key for harmonising heterogeneous activity names (and thus facilitates comparisons that are otherwise noise-prone at the activity level). We follow prior large-N LCA work that aggregates products to analyse cross-category patterns (e.g., Laurenti et al., 2023), and rely on the CPC/ISIC fields available in ecoinvent v3.x (Wernet et al., 2016).

Operationally, each activity was assigned a category and sub-category from CPC ranges, with explicit overrides for edge cases. Where CPC ranges overlap, later rules supersede earlier ones (e.g., plastics/rubber overrides chemicals). The resulting alignment used in the study is:

- **AgriForeAnim**
  - Agricultural & forestry products: CPC 00000–01999, 03000–03999, 39000–39999
  - Live animals, fish & their products: CPC 02000–02999, 04000–04999
- **ProcBio**
  - Food & beverages, animal feed: CPC 21000–23999, 42000–42999
  - Textile: CPC 26000–28199
  - Wood, straw & cork: CPC 31000–31999 (plus CPC 38100)
  - Pulp & paper: CPC 32000–32999 (plus CPC 38450→Textile)
- **OreMinFuel**
  - Ores, minerals & fuels: CPC 11000–17999, 33000–33999, 60000–69999

- **Chemical**
  - Chemical products: CPC 18000–18999, 34000–34699, 34800–35499
- **PlastRub**
  - Plastics & rubber products: CPC 34700–34799, 35500–36999
- **GlasNonMetal**
  - Glass & other non-metallic products: CPC 37000–37999
- **MetalAlloy**
  - Basic metals & alloys (incl. semi-finished): CPC 40000–41999
- **MachElecTrans**
  - Metal/electronic equipment & parts: CPC 43000–48999, 49941–49999 (plus CPC 38150→Furniture)
  - Transport vehicles: CPC 49000–49940
- **Construction**
  - Construction: CPC 53000–57999
- **Services**
  - Material recovery & waste management services: CPC 89000–94999

This scheme supports like-for-like comparisons of waste/material footprints and LCIA endpoints at multiple aggregation levels, while preserving traceability back to the underlying CPC codes (and activity Ids).

2.5 Calculations with LCIA and Waste and Resource Footprint methods

2.5 Calculations with LCIA and waste/material footprint methods

We computed, for every activity–year–scenario combination, (i) the T-reX inventory-based footprints—total waste, hazardous waste, and a panel of material footprints (individual materials and grouped classes)—and (ii) three ReCiPe 2016 (H) endpoint indicators: human health damage ($DALY \cdot kg^{-1}$), ecosystem damage ($species \cdot year \cdot kg^{-1}$), and resource scarcity ($USD2013 \cdot kg^{-1}$) (Huijbregts et al., 2016). T-reX methods operate as pseudo-LCIA: targeted technosphere exchanges are mirrored to auxiliary methods and summed per activity, preserving full traceability to exchanges and categories. For LCIA, foreground inventories were characterised against ReCiPe2016(H) without normalisation or weighting.

To reveal patterns across levels of aggregation, we report: activity-level values; sub-sector statistics (median and interquartile range across activities mapped to the same CPC-derived sub-category); sector statistics (median/IQR across sub-sectors); and database-wide totals (sums of footprints; medians for LCIA). Temporal and scenario dynamics were expressed as percentage change relative to 2020 and scenario deltas (e.g., SSP5–SSP1 at fixed year), with 95 % bootstrap confidence intervals at the sub-sector and sector levels (1 000 resamples, clustered by activity to avoid pseudo-replication). To limit undue leverage, we winsorised the upper 1 % of each footprint distribution and propagated this rule consistently across years and scenarios. All calculations were repeated for each prospective database variant to ensure like-for-like comparisons (McDowall et al., 2025; [REF: premise version/commit]).

This design allows direct comparison of sectors to sectors, activities within sub-sectors, and scenario-conditioned trends while keeping the link back to underlying exchanges—critical when interpreting divergences between LCIA damage and inventory-based waste/material signals.

3 Results (2500 words)

4 Discussion (1500 words)

What this study adds

Strengths of the approach

Limitations and caveats

Outlook and use

5 Conclusions and recommendations (500 words)

Supplementary Material

The supplementary material supplied in the appendices of this manuscript contain the following sections:

S1.

Data availability

All publicly available data related to this manuscript is available in online repositories hosted by Zenodo (https://doi.org/10.5281/zenodo.16995460) and Github (https://github.com/Stew-McD/T-reX_LCA-MacroStudy)

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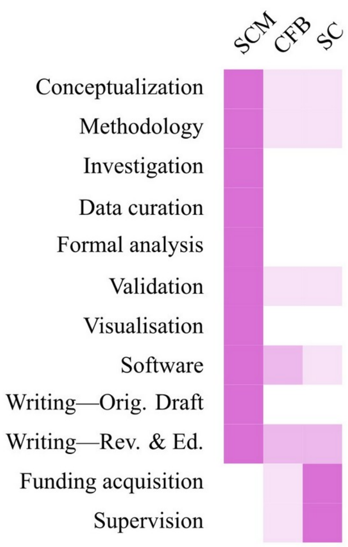
CRediT authorship contribution statement

Stewart Charles McDowall: Conceptualisation, Methodology, Investigation, Data curation, Formal analysis, Validation, Visualisation, Writing: original draft, Writing: review & editing, Visualisation.

Carlos Felipe Blanco: Conceptualisation, Methodology, Validation, Writing: review & editing, Funding acquisition, Supervision.

Stefano Cucurachi: Conceptualisation, Methodology, Validation, Writing: review & editing, Funding acquisition, Supervision.

CRediT authorship visualisation



Declarations

Competing interests

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.

Open access

Use of artificial intelligence

The authors declare that no generative artificial intelligence tools were used in the generation of the research data or results reported in this paper. Generative AI was used solely to assist in the editing and refinement of the manuscript text, with all content reviewed and approved by the authors.

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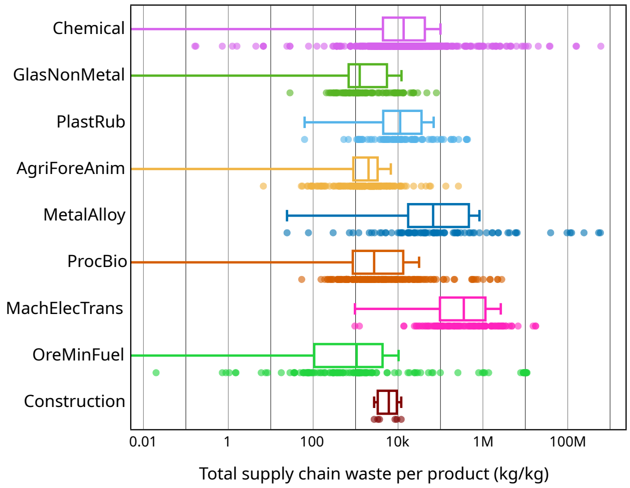
Tables

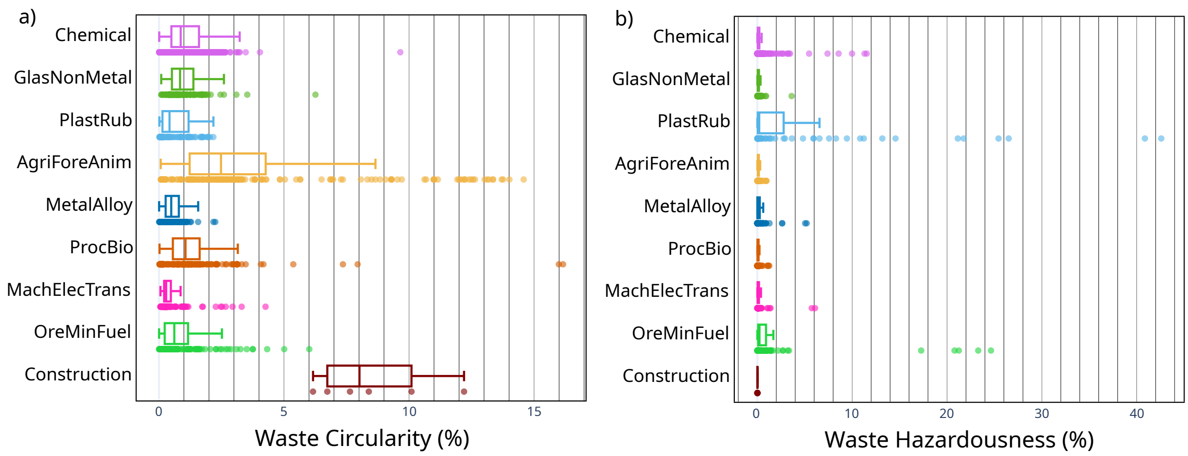
Figure Captions

Figures

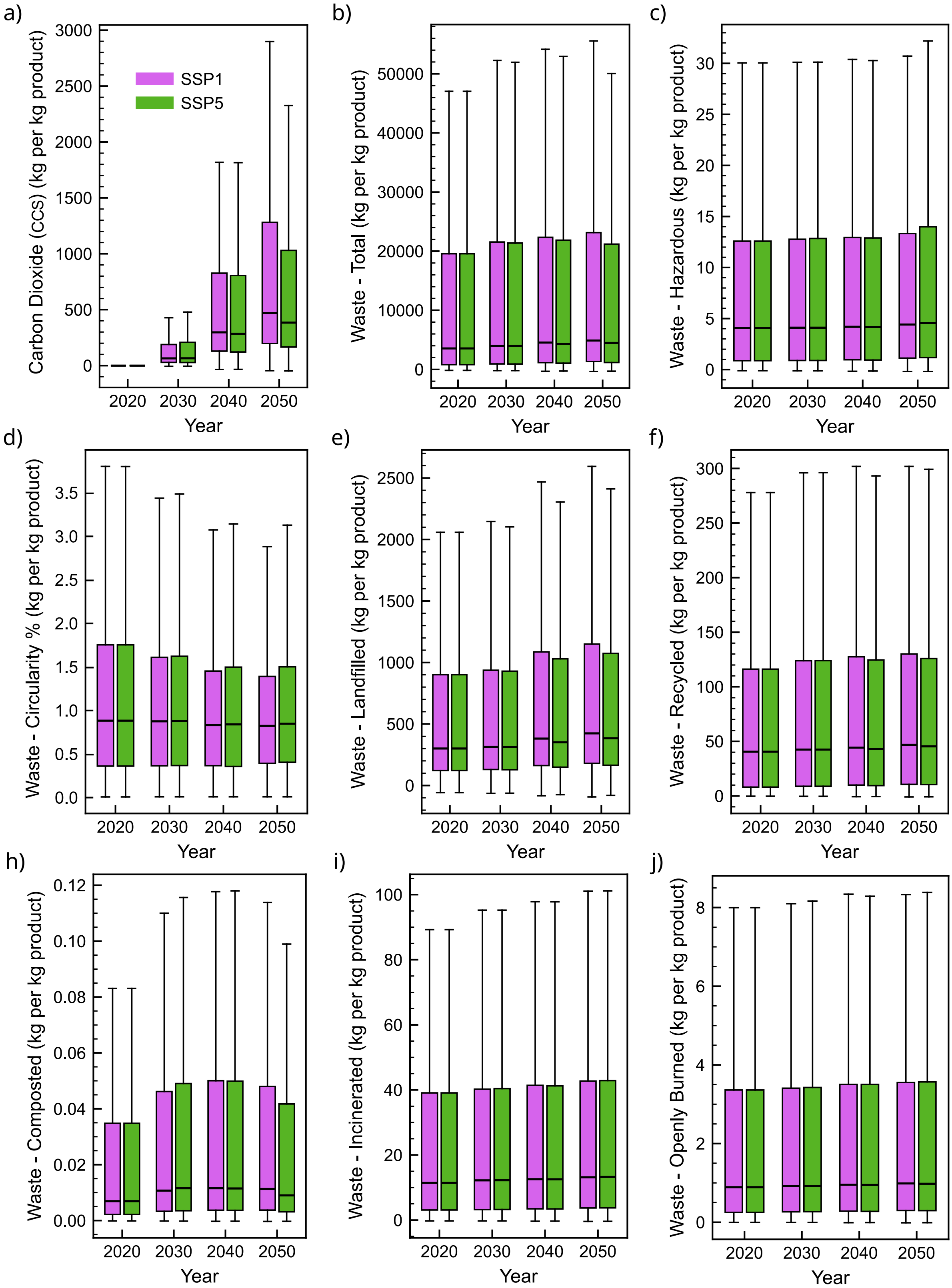
1.


Chemical
GlasNonMetal
PlastRub
AgriForeAnim
MetalAlloy
ProcBio
MachElecTrans
OreMinFuel
Construction
0.01
1
100
10k
1M
100M
Total supply chain waste per product (kg/kg)

2.


a)
Chemical
GlasNonMetal
PlastRub
AgriForeAnim
MetalAlloy
ProcBio
MachElecTrans
OreMinFuel
Construction
0
5
10
15
Waste Circularity (%)
b)
Chemical
GlasNonMetal
PlastRub
AgriForeAnim
MetalAlloy
ProcBio
MachElecTrans
OreMinFuel
Construction
0
10
20
30
40
Waste Hazardousness (%)

362 3.


a)
b)
c)
d)
e)
f)
h)
i)
j)
SSP1
SSP5
Carbon Dioxide (CCS) (kg per kg product)
Waste - Total (kg per kg product)
Waste - Hazardous (kg per kg product)
Waste - Circularity % (kg per kg product)
Waste - Landfilled (kg per kg product)
Waste - Recycled (kg per kg product)
Waste - Composted (kg per kg product)
Waste - Incinerated (kg per kg product)
Waste - Openly Burned (kg per kg product)
Year
2020
2030
2040
2050