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Review

Circular economy modelling for climate change mitigation: A review of empirical evidence and modelling approaches

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ABSTRACT

Circular economy (CE) measures can play a role in reducing greenhouse gas (GHG) emissions, especially in material- and energy-intensive sectors. Yet, their representation in GHG mitigation pathways is still not well captured in climate change mitigation models. To support modelling efforts towards better CE representation, two reviews were conducted: (1) the empirical evidence on the GHG mitigation potential of CE strategies across material supply and demand sectors and R-strategies, and (2) the current modelling approaches used to assess these strategies. Findings show that, while most studies focus on recycling, increasing attention is given to upstream strategies such as material substitution, design for reuse, and service-based business models. Important gaps remain, particularly around Refuse, Rethink, behavioural factors, rebound effects, as well as synergies and trade-offs with climate policy. Industrial ecology methods provide a detailed material flows representation but lack feedback mechanisms and economic dynamics. In contrast, GHG mitigation models offer broader system coverage but often simplify materials and CE dynamics. Better alignment between methods is needed, including shared definitions, improved data, and more collaboration across modelling communities. Strengthening the modelling of CE strategies can support policy-relevant assessments of CE's contribution to achieving global climate goals.

Acronyms

ABM	Agent based model
CDR	Carbon Dioxide Removal
CE	Circular Economy
CFRP	Carbon-Fibre Reinforced Polymers
CGE	Computable General Equilibrium
COP	Conference of the Parties
CPA	Classification of Products by Activity
CSC	Closing Supply Chains
d-MFA	Dynamic Material Flow Analysis
EEIO	Environmentally Extended Input Output

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EoL	End-of-Life
ESM	Energy Systems modelling
EU	European Union
EW-MFA	Economy-Wide Material Flow Analysis
EXIOBASE	Environmentally Extended Input-Output Base
GHG	greenhouse gas
GTAP	Global Trade Analysis Project
HS/SITC	Harmonized System/Standard International Trade Classification
IAM	Integrated Assessment Modelling
IE	Industrial Ecology
IEA	International Energy Agency
IEDC	Industrial Ecology Data Commons
ILCD	International Reference Life Cycle Data System
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel for Climate Change
ISIC	International Standard Industrial Classification
LCA	Life Cycle Assessment
LED	Low Energy Demand
MFA	Material Flow Analysis
MRIO/MRIOs	Multiregional Input-Output
MSW	Municipal Solid Waste
NDCs	Nationally Determined Contributions
OECD ICIO	OECD Inter-Country Input-Output
PLE	Product Lifetime Extension
RE	Resource Efficiency
RWM	Residual Waste Management
SD	System Dynamics
SSP	Shared Socioeconomic Pathway
UNFCCC	United Nations Framework Convention on Climate Change
VRP	Value-Retention Processes
WIOD	World Input-Output Database

1. Introduction

The circular economy (CE) concept has gained traction among policy-makers (Calisto Friant et al., 2021), and practitioners (Massaro et al., 2021) as a way to transition towards more sustainable production and consumption patterns, becoming a growing research field (Geissdoerfer et al., Feb. 2017; Kirchherr et al., 2023). The circular economy refers to a systemic transformation of the traditional and linear throwaway economy, aiming to narrow, slow, and close material loops. Narrowing loops aim to reduce material and energy use per unit of service; slowing loops focus on extending product lifetimes through repair and reuse; while closing loops refer to recycling materials at end-of-life to reduce reliance on virgin materials (Ellen MacArthur Foundation, 2013; Potting et al., 2017). As such, a circular economy decouples natural resource consumption from economic output (McCarthy et al., 2018) and can be applied to different scales from macro (global, national or regional level) to *meso* (eco-industrial parks) and micro (single firms, or products) level.

While CE strategies have long been discussed (McDowall et al., 2017), only recently the potential contribution of CE to greenhouse gas emissions (GHG) mitigation has come into focus (Cantzler et al., 2020; Hertwich et al., Dec. 2019; IRP 2024). This interest arose since the production of materials such as steel, cement, aluminium, and primary chemicals is energy- and emissions-intensive, driving its share of global GHG emissions to grow from 15 to 23% between 1990 and 2015 (Hertwich, 2021). Thus, CE policies could effectively complement traditional climate policies that focus on decarbonisation and energy efficiency (Bleicher and Pehlken, 2020). The mitigation potential of CE has been acknowledged by policymakers, as shown in the commitment of the European Union (EU) to promoting a CE as part of its overall objective to achieve climate neutrality by 2050 and meet the Paris Climate Agreement goals (European Commission 2021), which is also emphasised in the EU Circular Economy Action Plan (European Commission 2020). Moreover, recent policy frameworks also promote CE, including the European Green Deal, and digital transition (European Commission 2015).

With the world off track to meet the climate targets of the Paris Agreement (United Nations Environment Programme 2024), CE strategies – complementary to energy decarbonisation – are gaining importance but remain insufficiently researched (Bashmakov et al., 2022). While significant work has been done in the industrial ecology field to quantify emissions reduction from CE measures, particularly through life cycle assessment (LCA), material flow analysis (MFA), and input-output analysis (IOA) (e.g., (Pauliuk et al., 2021; Milford et al., 2013; Wolfram et al., 2021)), these methods and models often lack explicit and dynamic representation of the energy system and its technologies. This limits their ability to assess climate policies and the interaction between CE and the energy transition (Businge and Mazzoleni, 2023). On the other hand, GHG mitigation policy and strategies have been widely supported by scenario-based assessments developed by process-based and macroeconomic Integrated Assessment Models (IAM), extensively used by the Working Group III (WGIII) of the Intergovernmental Panel for Climate Change (IPCC) (Intergovernmental Panel On Climate Change, 2023). While these models explore in detail the technological options (Bashmakov et al., 2022; Intergovernmental Panel On Climate Change, 2023) or macroeconomic outcomes (McCarthy et al., 2018), with broad coverage of economic sectors and their interrelations, they generally lack the granularity and stock-flow-service nexus representation needed to assess circularity (Pauliuk et al., 2017; Wiedenhofer et al., 2024; Magalar et al., 2026).

The link between material and energy service provision introduces a complex network of synergies and trade-offs between climate and resource policy. Capturing the contribution of CE to GHG mitigation, therefore, requires representing material stocks and circular flows across multiple sectors, materials, and regions, while consistently accounting for socio-economic, technological, and environmental effects. Within this context, key analytical questions need to be answered. For instance, how do emissions-intensive material stocks and flows evolve over time across regions and under different scenarios? How do CE measures affect both material stocks and long-term energy/emissions trajectories? To what extent rebound effects of CE measures reduce their climate mitigation potential? What is the net contribution of CE to achieving global climate targets, considering rebound effects and biophysical limits?

Moreover, the multiple interpretations of CE add definitional issues to the challenge of quantifying the potential of CE for GHG mitigation (Kirchherr et al., 2017; Kirchherr et al., 2023; Velenturf and Purnell, 2021). The need to bridge diverse modelling communities in a CE harmonised theoretical and modelling framework becomes evident (Pauliuk et al., 2017), and standardised definitions ensure that various models can effectively communicate and integrate their findings.

A growing body of literature has been examining the relationship between CE and climate change mitigation from different perspectives. Cantzler et al. (2020) Cantzler et al., 2020, for instance, performed a systematic review of the scientific literature assessing the potential of CE to reduce GHG emissions (Cantzler et al., 2020). Similarly, Wiedenhofer et al. (2025) analysed the empirical evidence of mitigation potential of CE measures at the macro-level (Wiedenhofer et al., 2025), while Lima et al. (2024) assessed the GHG mitigation potential of CE with a specific focus on construction materials and their implications for climate mitigation modelling (Lima et al., 2024). More recently, Magalar et al. (2026) reviewed the representation of circular economy policies within IAM, identifying key gaps that limit the evaluation of CE strategies in climate mitigation scenarios and highlighting priority areas for improvement (Magalar et al., 2026).

Despite these advances, the literature remains fragmented. Studies focusing on empirical mitigation potential (Cantzler et al., 2020; Wiedenhofer et al., 2025; Lima et al., 2024) rarely examine how these insights can be translated into climate mitigation modelling frameworks; conversely, modelling-focused studies (e.g., (Magalar et al., 2026)) primarily assess the representation of CE strategies within IAM without considering broader empirical evidence and their relevance for mitigation. This paper addresses this gap by combining two complementary reviews: (i) a synthesis of the empirical evidence on the mitigation potential of CE measures across end-use sectors using a harmonised narrow-slow-close terminology (Bocken et al., 2016), and (ii) an assessment of the ability of existing modelling approaches, beyond IAM, to represent and quantify the GHG mitigation potential of CE. By jointly analysing empirical evidence and modelling capabilities, the innovative contribution of this study lies in identifying which CE strategies reported in the literature as having the highest mitigation potential remain insufficiently represented in current models. This allows linking modelling gaps directly to empirically relevant CE measures across sectors and R-strategies, thereby providing climate modellers with targeted recommendations for improving circularity representation in the context of GHG mitigation. The following sections present the method used (Section 2), the results of the review on empirical evidence of CE measures potential for GHG mitigation

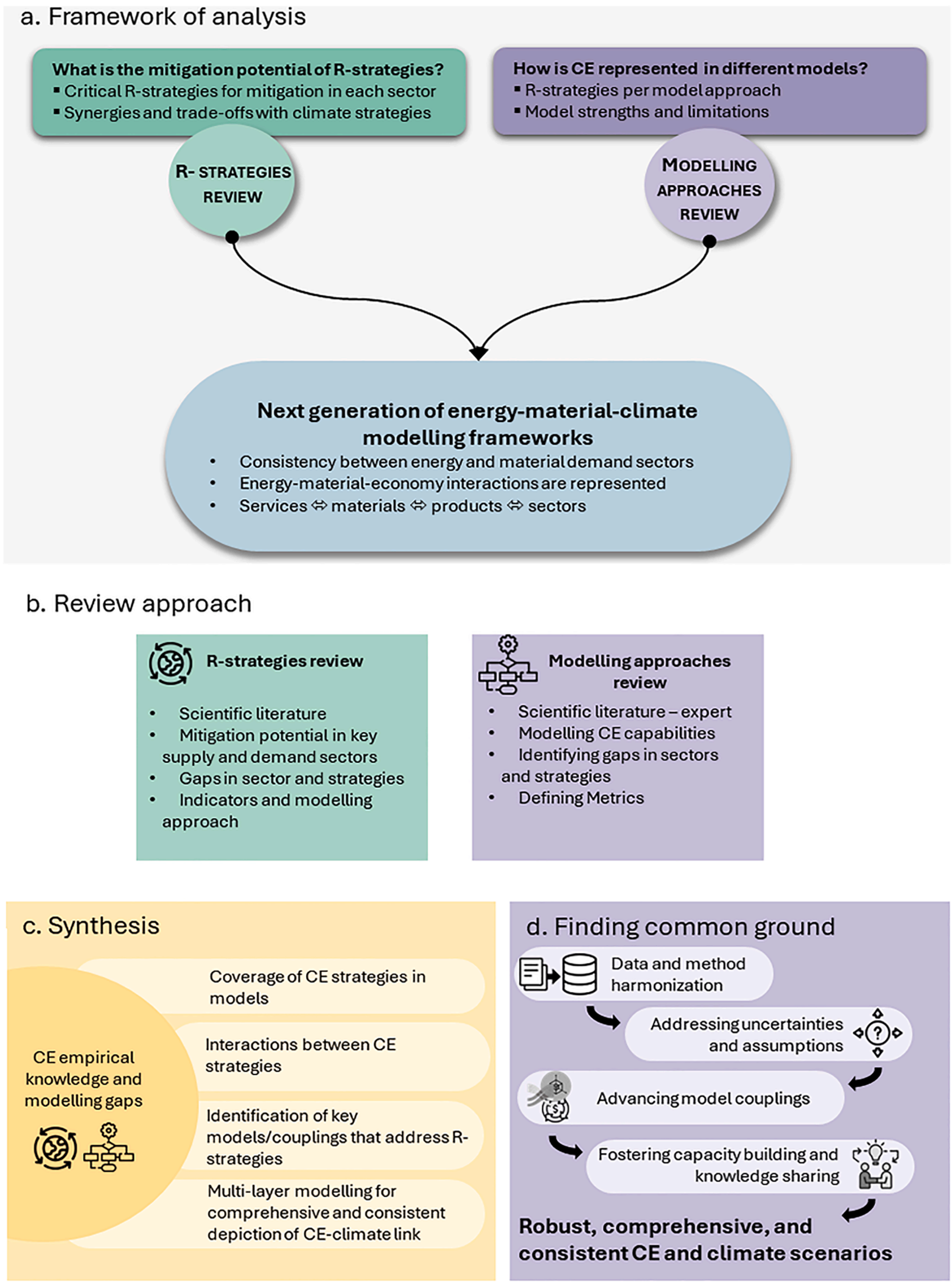

Fig. 1. Synthesis of the methodological approach.

(Section 3), and the review on current modelling approaches used to assess CE measures (Section 4). Lastly, a synthesis of these results are presented and suggestions for future model development are provided (Section 5). Fig. 1

2. Methods

Given the diversity of CE strategies, sectors, and modelling approaches, as well as metrics to quantify their mitigation potential, this study adopts a systematised review design rather than a fully systematic review. This approach allows structured literature selection while retaining flexibility to incorporate expert knowledge and grey literature, which is particularly relevant for emerging modelling practices in climate mitigation. From a climate change modelling perspective, the priority lies in identifying sector-specific CE strategies with the highest GHG mitigation, and assessing whether current models can represent those measures. To support this goal, we conducted two targeted literature reviews:

- Empirical evidence of CE measures potential for GHG mitigation
- Current modelling approaches used to assess CE measures

In these reviews, we define CE strategies as any intervention implemented at any stage of a supply chain that aims to ultimately reduce the extraction and processing of primary resources. They can take effect either by policies implemented by governments or regulatory bodies; changes in individual or collective behaviour or societal norms; or initiatives by businesses, organisations, and communities. In this framework, narrowing strategies refer to approaches that reduce the resources and energy required by economic activities through reductions in material and energy inputs across production and consumption systems; slowing strategies aim to extend product lifetimes, for instance through reuse, maintenance, repair, and upgrading, thereby delaying resource flows through the economy; while closing strategies focus on retaining materials within the economic system namely by enabling recycling and recovery through appropriate product and system design.

For the empirical evidence review, a systematised approach was used to assess CE mitigation potential across material demand (Table 1) and supply (Table 2) sectors. Many studies analysed CE measures considering both material demand and supply sectors, which was accounted for accordingly. Different products and subsectors in each group were considered regardless of how the system was defined in the study.

The search was based on Scopus and Web of Science using keyword combinations covering CE strategies, GHG mitigation, and sector-specific terms. Full search strings are provided in Supplementary Table 1. A first screening based on titles and abstracts applied the following inclusion criteria: studies must (i) establish an explicit link between a CE measure and GHG reduction, (ii) focus on material- rather than energy-related drivers of mitigation, and (iii) address technologies at commercially relevant maturity levels, if applicable reduction. Studies limited to conceptual or definitional discussions of CE, lab-scale innovations, or exclusively energy-related measures (e.g., waste-to-energy, fuel switch) were thus excluded. After abstract screening, 2036 records were retained for full-text review. Sector leads then selected a minimum of ten studies per sector, prioritising narrow and slow over close strategies, as recycling is an established measure commonly addressed in energy-related studies. The studies deemed most representative of CE implementation in each sector were chosen for coding. Moreover, a subsequent snowball sampling round, supported by expert inputs from the Industrial Ecology and IAM communities to identify additional relevant studies and fill gaps in strategies and sectors, resulted in a final sample of 186 papers coded. Each article was coded independently using a structured coding table (presented in Supplementary Information). The full list of reviewed articles is provided, as well as the details on selection/exclusion criteria is presented in the Supplementary Information.

The coding table consisted of columns covering bibliographic details (e.g., authors, title, year, DOI), methodological features (e.g., research design, modelling approach), system characteristics (e.g., geographic scope, system level, material system, product system), and circularity dimensions (e.g., R-strategy, CE measure, life cycle stage). Moreover, assessments of CE measure implementation potential were recorded, as well as its related GHG mitigation potential, and any reported social/economic/environmental co-benefits.

When available, definitions and metrics were extracted directly from the articles; qualitative interpretations were also documented. Studies focusing on the micro-, meso-, or macro-level were considered to capture the broadest possible spectrum of CE measures per sector. However, the diversity of systems analysed, and methods applied resulted in GHG mitigation metrics that are not directly comparable across sectors or products. We acknowledge this as a limitation of this work and discuss it in more detail in Section 5.

The CE modelling approaches review focused on identifying how CE is currently represented in models assessing GHG mitigation. It focused on industrial ecology models, climate change mitigation models, and other quantitative modelling approaches. Literature was identified mostly through expert inputs, particularly for IAM and MFA experts who co-author this article, and snowballing informed by prior review studies, but also through Scopus and Web of Science queries combining terms like “CE modelling” and “climate mitigation”. Studies were included if they quantified effects from CE measures implemented at a macro scale, such as material and emission reductions. Assessments based on qualitative indicators and surveys were excluded.

The methodological choice of combining two complementary literature reviews was important in that it allowed identifying the gaps and robust evidence of the mitigation potential of CE measures

Table 1
Material demand sectors and subsectors considered in this study.

Material demand sectors	Subsectors/products
Vehicles	Passenger
	Freight
Buildings[¥]	Residential
	Non-residential
Consumer goods	Appliances
	Furniture
	Packaging
Infrastructure	Transport infrastructure
	Energy infrastructure
Machinery	Industrial
	Waste management
	Mining
	Agricultural

[¥] The buildings sector was excluded from the systematised review because it has been comprehensively covered in recent reviews (Gallego-Schmid et al., 2020; Hertwich et al., 2019). However, Supplementary Information provides a synthesis of the findings of these reviews.

Table 2
Material supply sectors as covered in this study.

Material supply sectors	Materials
Ferrous metals	Iron and Steel
Non-ferrous metals	Aluminium
	Copper
Non-metallic minerals	Cement
	Ceramics
	Glass
	Aggregates
Chemicals	High-value chemicals
	Ammonia
	Methanol
	Refinery Products

comprehensively across sectors, while evaluating whether current models have the ability to represent the strategies. The mismatches between empirical knowledge and modelling capability could then be translated into a prioritised set of model development needs that would allow them to design scenarios that account for CE contribution to GHG mitigation.

Table 3 summarises the research questions, methodological approaches, scope, search strategy, selection and exclusion criteria in each review. Together, these reviews aim to identify sectoral empirical knowledge gaps and modelling limitations to inform improved CE representation in climate mitigation assessments.

Table 3
Research questions, methods, scope, strategy, selection and exclusion criteria related to each review performed.

	Review on empirical evidence of CE measures potential to GHG mitigation	Review on current modelling approaches used to assess CE measures
Research question (s)	What is the current evidence of GHG mitigation potential of enhancing circularity in various sectors, products, and services? Which sectors and strategies have been explored more thoroughly, and where do we lack information on this potential?	How effectively do current models represent circularity, and what are their limitations and complementarity? How can we improve their representation of CE for GHG mitigation based on the current empirical knowledge and gaps in policy?
Method	Systematised approach followed by a semi-structured snowball sampling process. A minimum of 10 studies per sector was defined.	The analysis of the existing modelling approaches to quantify CE is supported by a snowball process driven by existing literature review studies (Walzberg et al., 2021; Merli et al., 2018; Sassanelli et al., 2019)) and expert knowledge for the case of IAM
Scope	• Material demand sectors[¥]: Transport, Consumer goods, Infrastructure, and Machinery. • Material supply sectors: Iron and Steel, Non-ferrous metals, Non-metallic minerals and Chemicals	- Industrial ecology models- Climate change mitigation models- Other
Search strategy[†]	• Queries in Scopus and Web of Science: TITLE-ABS-KEY ({CE measures keywords} + {Climate change mitigation keywords}) AND TITLE {sector-specific keywords} • Snowballing based on sector experts' assessment	- GHG mitigation modelling literature based on expert knowledge- Queries in Scopus and Web of Science: TITLE-ABS-KEY ({"climate mitigation modelling" AND ["CE model*" OR "CE quant*"]} + {"review"})- Snowballing processes
Selection criteria	• Studies that make a specific link between GHG reduction and CE measure implementation • Focus on material-related rather than energy-related measures • Priority given to narrow and slow strategies, as close strategies are usually more commonly found in the energy/climate literature • Peer-reviewed studies but also grey literature	- Studies focusing on CE quantification- Review of existing CE quantification potential (e.g., materials reduction, GHG emissions reduction)- Priority given to macro-scale CE modelling
Exclusion criteria	• Studies that discuss concepts and definitions of CE • Studies about technology innovations in lab scale (low maturity/proof of concept stage)	Quantification based on indicators or participatory methods (e.g., analysis of surveys)

[¥] The buildings sector was excluded from the systematised review because it has been comprehensively covered in recent reviews (Gallego-Schmid et al., 2020; Hertwich et al., 2019). However, the Supplementary Results section provides a synthesis of the findings of these reviews.
[†] Keywords per sector can be found in the Supplementary Table 1.

Exclusion criteria were developed to ensure that all reviewed studies were relevant to assessing the empirical evidence of CE contribution to GHG reduction or its representation in modelling frameworks. Accordingly, two main categories of studies were excluded. First, studies focusing exclusively on conceptual, definitional, or normative discussions of the CE were considered out of scope. While these contributions are relevant for theoretical debates, this is not the core objective of this work. We nevertheless aim to indirectly contribute to these conceptual discussions by providing a structured synthesis of R-strategies according to the life cycle stage of the material that it affects (in Table 4), without engaging in an extensive theoretical debate. Second, studies assessing technology innovations at laboratory scale were also considered out of scope due to the high uncertainty regarding scalability and real world performance.

Moreover, as it is not always clear what the distinction is between a CE and an energy/climate measure (e.g. modal shift, bioeconomy), we prioritised studies that had a material demand reduction effect as the primary driver of GHG mitigation. For instance, CE measures for agriculture/forestry sectors were considered out of the scope of this study despite the potentially relevant role of biomass reported in the climate literature and the links between bioeconomy and CE (e.g., as presented in the European Bioeconomy Strategy (Directorate-General for Research and Innovation (European Commission) 2018)). Moreover, papers that exclusively cover energy-related CE measures, such as energy recovery, waste-to-energy, and fuel switch, were given less priority, given that these topics are extensively covered in the energy modelling literature (Bruno et al., 2021; Demetrious and Crossin, 2019; Chandel et al., 2012). Similarly, CE focused on critical material and their potential to disrupt low-carbon supply chains through restriction of access to materials was considered out of the scope, as our focus was on mitigation potentials in bulk materials (Table 2). In this study, bulk materials are defined as high production volume materials whose primary production is both energy- and carbon-intensive and therefore makes a substantial contribution to global GHG emissions. This includes iron and steel, non-metallic minerals (e.g., cement and lime), non-ferrous metals (e.g., aluminium), and primary chemicals (e.g., ammonia, methanol, ethylene and propylene).

Therefore, rather than aiming for a comprehensive and systematic review, this systematised approach was designed to (1) identify key supply and demand CE measures for GHG mitigation, and (2) to support the development of a comprehensive, robust and consistent analytical framework to understand the GHG mitigation potential of CE.

Table 4 presents the hierarchy of CE strategies together with representative examples, corresponding life cycle stages, and their drivers of GHG mitigation. The "R-strategy" column was based on the 10R framework from R0 Refuse to R9 Recover from Potting et al., (2017) (Potting et al., 2017), and harmonised into the three overarching strategy groups following the narrow-slow-close hierarchy (Zorpas, 2020). Narrow strategies reduce the material input required to deliver a given service, slow strategies extend the service life of products and components, and close strategies aim to loop materials back into production through recycling or energy recovery, thereby reducing primary material extraction. Within this structure, Reduce (R2), Reuse (R3), and Recycling (R8) were subdivided into to sub-strategies to reflect the different mechanisms through which they operate and the different system components they affect. For instance, while all Reduce strategies aim to reduce overall material use per service unit, lightweighting and downsizing affect product manufacturing without changing the demand for products, while modal shift affects the demand for products itself. These subcategories are relevant because they differ in their implications for stock dynamics, technological substitution, rebound effects, and modelling representation. For each R-strategy, the table identifies the corresponding material life cycle stage, the main driver of GHG mitigation, and whether the strategy directly affects energy- and/or material-related emissions. This classification supports a more precise

Table 4
Definition and examples of Narrow, Slow, and Close R-strategies.

CE strategy	R-strategy	Example of CE measures	Material life cycle stage	Driver(s) of GHG mitigation	Direct effects on energy-related emissions[¥]?	Direct effects on material-related emissions*?
Narrow	R0 Refuse	Avoid traveling by plane	Service demand	↓ Service demand	Yes	Yes
	R1 Rethink	The 15-minute city, telework	Service provision	↔ Service provision	Yes	Yes
	R2 Reduce	Increase in industrial material productivity	Product demand, use, and manufacturing	↔↓↑ Product demand	Maybe	Yes
	R2a: Modal or type shift in service provision	Meat replacement products, transport mode shift, building type shift	Product demand	↔ Product mode or archetype	Yes	Yes
	R2b: Business model shift in service provision	Product as a service, sharing economy solutions	Product use	↓ Product intensity of use	Yes	Yes
	R2c: Downsizing: Shift to smaller products more adequate to demand	Smaller vehicles that fit the typical use pattern	Product manufacturing	↔ Product design (within archetype)	Yes	Yes
	R2d: More intense use	Smaller living space through co-habitation and shared spaces	Product manufacturing	↑ Product intensity of use (in design)	Yes	Yes
	R2e: Product lifetime extension	Longer vehicle or product lifetime through better design or repairability	Product manufacturing	↑ Product lifespan (in design)	Yes	Yes
	R2f: Product lightweighting	Lighter products through better design	Product manufacturing	↓ Total material weight (per unit)	Yes	Yes
	R2g: Material substitution	Lighter products through material substitution	Product manufacturing	↔ Product design	Yes	Yes
	R2h: Fabrication yield improvement	Higher fabrication yields, reduced trimming losses etc.	Product manufacturing	↑ Product manufacturing efficiency (reduced losses)	No	Yes
	R2i: Fabrication scrap diversion	*Re*-use of fabrication scrap without remelting	Product manufacturing	↑ Product manufacturing efficiency (reuse of scrap)	No	Yes
Slow	R3a: *Re*-use of entire products	Second-hand clothing or appliance	Product use	↑ Product lifespan	No	Yes
	R3b: *Re*-use of components	Vehicle traction batteries used as stationary energy storage	Product use	↑ Product component lifespan	No	Yes
	R4 Repair	Repair of broken mobile phones or white goods	Product use or End-of-Life (EoL)	↑ Product lifespan	No	Yes
	R5 Refurbish	Building insulation improvement	Product use or EoL	↑ Product lifespan	No	Yes
	R6 Remanufacture	Turn product components, like from white goods, into new products with non-destructive material re-use (no remelting)	Product use or EoL	↑ Product lifespan	No	Yes
	R7 Repurpose	Convert office building into living space	Product use or EoL	↑ Product lifespan	No	Yes
Close	R8 Recycle	Product materials from scrap, not from virgin resources like ore	Material EoL	↓ Primary material demand	Yes	Yes
	R8a: Closed loop recycling	Remelting of scrap into same quality group	Material EoL	↓ Primary material demand (same quality)	Yes	Yes
	R8b: Cascading or downcycling	Contaminated high-quality aluminium scrap turned into cast alloy	Material EoL	↓ Primary material demand (lower quality)	Yes	Yes
	R9 Recover	MSW incineration, Waste-to-Energy	Material EoL	↑ Energy recovery	Yes	Yes

↔: Switch, ↓: Reduction, ↑: Increase.

[¥] Emissions from operational fuel use (e.g., fuel use in cars, heating/cooling appliances, cooking, lighting); * Emissions from primary/secondary material production and raw material mining, including process emissions and emissions from operational fuel use in those activities.

mapping between empirical mitigation evidence and the modelling approaches required to represent each mechanism.

3. R-strategies in climate-relevant sectors

The sectoral, system-level, and R-strategy coverage of the analysed literature are presented in

Fig. 2. Bulk materials such as steel, aluminium, plastics, and cement were found to have more relevance in the circular measures literature, with >19 studies each (Fig. 2a). Studies considering micro- (45% of all studies considered for in-depth review), meso- (18%), and macro- (37%) level systems were analysed (Fig. 2b) (see SI for the full list of articles coded).Narrow (63%), Close (24%) and Slow (13%) strategies were reviewed across sectors (Fig. 2c). LCA and MFA are the modelling methods more applied for these circularity assessments (Fig. 2d). Reduce strategies were found relevant in most of the sectors (Fig. 2e). Rethink strategies are directly linked to service provision and were more prevalent in material demand than in supply sectors. In contrast, recycling strategies were more common in supply sectors. Therefore, while we find extensive research in transforming basic material industries' (supply) to increase recycling as a strategy to reduce GHG emissions, the suitability of product designs (demand) for facilitating effective material recycling is less well understood.

3.1. Circularity can contribute significantly to reducing GHG emissions and complement energy-related measures

Our review reveals that steel and cement are the materials most studied regarding CE (32% of the total sample). This is due to the scale of global production of steel (~1900 Mt yr^{-1}) and cement (~4100 Mt yr^{-1}), their extensive use in buildings and vehicles, and their high emission intensity (Edelenbosch et al., 2024; Pauliuk et al., 2024). Implementing ambitious CE strategies could, for example, almost halve of global cumulative cement and steel demand until 2050 in the building sector

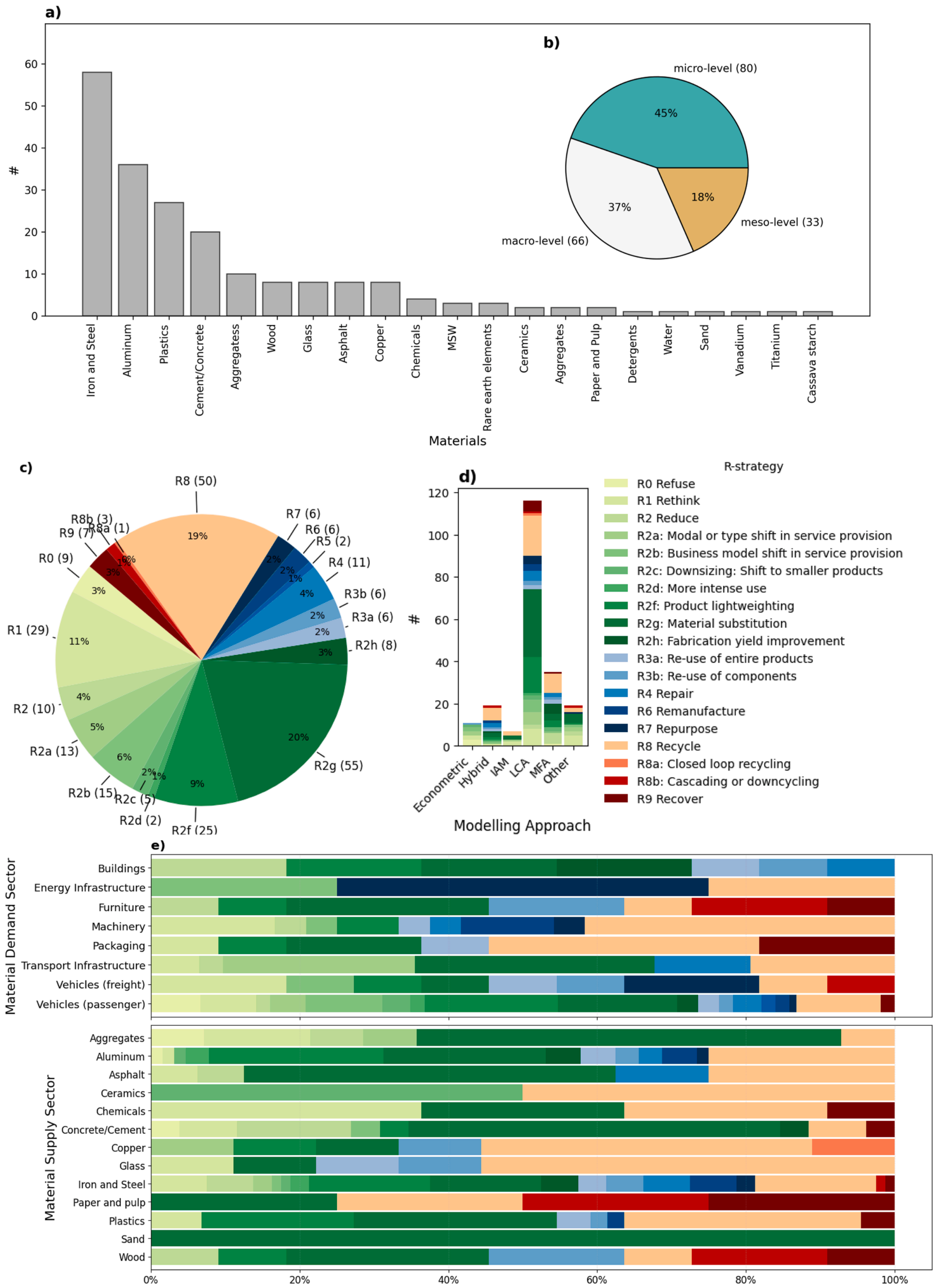

Fig. 2. Coverage of the papers analysed regarding materials and systems level (a), R-strategies (b), modelling approaches per R-strategy (c), and R-strategy per sector (d). In panels (b–d), each reported R-strategy was counted separately (i.e., multi-strategy mentions in a single study are counted as multiple entries). Percentage values mentioned in the text follow the same approach. Detailed information per sector can be found in Supplementary Results. MSW: Municipal Solid Waste.

(Pauliuk et al., 2024). The highest mitigation potentials for buildings are associated with lifetime extension (40% GHG savings (Cai et al., 2015)) and the use of alternative materials such as wood (up to 50% if biogenic carbon storage is considered (Ximenes and Grant, 2013; Göswein et al., 2021)). However, stock expansion, particularly in Global South countries, as well as limited availability of alternative materials, e.g. wood for construction, constrain such strategies (Pauliuk et al., 2024). Narrowing overall material demand, for example, by increasing the intensity of use (car-, ride-sharing for vehicles, and reducing floor space area per capita for buildings), or by lightweighting products, could in these cases even achieve higher material and emission savings (Pauliuk et al., 2021; Pauliuk et al., 2024). SI provides the contribution of circularity in reducing GHG emissions across material demand and supply sector, as well as the methods used and other relevant information.

Most studies report mitigation potentials for single sectors or products. However, economy-wide estimates are necessary to understand the global relevance of circularity, not only in terms of its relative contribution to global mitigation efforts, but also its capacity to offset residual emissions (i.e., remaining emissions after global net-zero are achieved) and to reduce reliance on carbon dioxide removal technologies (CDR). Residual CO_2 emissions reported by IAM scenarios consistent with the Paris goals are often between 5.8–18 $GtCO_2yr^{-1}$ in C1-C3[2] scenarios in 2050 (partly or fully compensated by carbon dioxide removal) (Lamb, 2024). The global circularity mitigation potentials in residential buildings and passenger vehicles have been reported to contribute with a 1.1–3.4 $GtCO_2yr^{-1}$ reduction by 2050, relative to corresponding baseline scenarios (Low Energy Demand (LED), SSP1, and SSP2) (Pauliuk et al., 2021). Current findings thus show that CE strategies could complement conventional mitigation approaches such as energy efficiency and switch to renewables, while reducing the need for emerging and unreliable CDR technologies (Edelenbosch et al., 2024).

3.2. The literature is concentrated on recycle with growing emphasis on reduce and rethink

Recycling remains the most common R-strategy in the literature (21% of all strategies mentioned), reflecting the reliance on end-of-pipe measures despite the focus of this study on Reduce and Rethink (Cantzler et al., 2020; Morseletto, 2020; Ranta et al., 2018) (see Fig. 3). While Narrow strategies are the most represented overall (

Fig. 2, 60%), detailed per-sector and per-strategy assessment shows that there is a higher focus on material substitution (R2g, 20.5%) and product lightweighting (R2f, 9.3%) within the Narrow strategy. For instance, substituting steel by high-strength steel, aluminium, magnesium alloys or carbon-fibre reinforced polymers (CFRP) in vehicles could reduce their weight between 16% and 55%, affecting both primary material demand and fuel use (Gonçalves et al., 2022; Kawajiri et al., 2020; Picatoste et al., 2022). Cement and steel substitution for wood in buildings is said to reduce embodied carbon as well as to store biogenic carbon (Churkina et al., 2020; D'Amico et al., 2021; Gustavsson et al., 2006). Some studies reported little or no significant consequences to agriculture production (Mishra et al., 2022), offering a far more substantial mitigation potential compared to the use of wood as fuel (Hart et al., 2021); others, on the other hand, argue that when accounting for the carbon prevented from accumulating in forests due to wood extraction, the climate benefits may be offset (Maierhofer et al., 2024) .

Other narrow strategies rely on modal/type shift in service provision (R2a, 4.8%), which are measures often assessed by climate and energy research on macro level, including IAMs and Computable General Equilibrium (CGE) models. On the other hand, the studies assessing R2g and R2f were found to rely more on modelling approaches with a focus on the micro level and concentrated on LCA (29% of R2g modelling studies, Fig. 3d). This shows that while material substitution is found relevant for GHG reduction, it is rarely assessed in macro-scale climate mitigation modelling given the complexity of modelling inter-material substitution based on service provision.

Beyond R2g and R2f, the Reduce strategy encompasses a broader scope of measures, primarily drawing from the material efficiency literature (Allwood et al., 2011), and include also business model shift (R2b), downsizing (R2c), more intense use (R2d), product lifetime extension (by design) (R2e), fabrication yield improvement (R2h), and fabrication scrap diversion (R2i) (Wolfram et al., 2021), (Huang et al., 2016; Winnett et al., 2017), which cover 11% of the sample (see Table 4). Increasing focus has been identified in business model shift (R2b), including innovative business models (e.g., city-wide bike-sharing schemes (McQueen et al., 2020; Teixeira et al., 2021; Zheng and Li, 2020), last-mile freight deliveries with e-bikes (Aryal et al., 2022; Matubatuba and De Meyer-Heydenrych, 2022; Pei et al., 2023)), and shared service provision (e.g., car-pooling, car-sharing, ridesharing (Asghari et al., 2022; Shaheen and Chan, 2016)).

Visibly, rethinking service provision (R1), i.e., delivery of services and functionality instead of a certain amount of a product, is gaining momentum in the CE for GHG mitigation literature (11% of the sample). This includes the redesign of transportation systems (e.g., via accessibility of daily routes, optimising bus systems or bus rapid transit (Matubatuba and De Meyer-Heydenrych, 2022) using digital data (Yu et al., 2020), or facilitating the last-mile from the public transport system to start and end point (Shaheen and Chan, 2016; Wang et al., 2021; Bürstlein et al., 2021)) and infrastructure (Mattinzioli et al., 2021; Wang et al., 2018), product substitution (e.g., fossil-based to biodegradable packaging (Casarejos et al., 2018; Spierling et al., 2018)), and increased industrial symbiosis (e.g., by exchanges of byproducts and off-gases (Axelson et al., 2021), (Bonoli et al., 2020), (Cravioto et al., 2021)).

The mitigation potentials are generally high in studies assessing Rethink measures on the demand side, but their explicit representation in physical models can be challenging. These models often lack access to reliable data, as evidenced by the low share of IAM and MFA (Fig. 3d

Fig. 2). In contrast, LCA (44%) was found to be the main modelling approach assessing this strategy.

Rethink measures were also found from a supply-side perspective. While in most cases not an active strategy, the carbon uptake due to cement carbonation over the lifetime (and beyond) of concrete products is reported to have a substantial role in cement's life-cycle carbon balances. Pade and Guimarães (2007) have found that crushing end-of-life concrete and exposing it to air could increase uptake of CO_2 to 50% (Pade and Guimaraes, 2007), while Xi et al. (2016) (Xi et al., 2016) found that 43% of the calcination-related cumulative CO_2 emissions from cement production between 1930 and 2013 was sequestered due to carbonation of cement materials over the same period in China. At a global scale, Cao et al., (2020) found that 30% of cumulative emissions would be offset from 2015 to 2100 (Cao et al., 2020). While these findings suggest that cement materials can significantly offset cement process emissions, subsequent studies have questioned the magnitude of this effects, which would largely depend on exposure conditions (e.g., humidity, surface area, CO_2 concentration) (von Greve-Dierfeld et al., 2020) as well as demolition practices and timing. Moreover, since carbonation only partly reabsorbs previously released process emissions, qualifying this as a circular economy strategy is highly questionable.

3.3. The scientific literature shifts towards material life cycle perspective

A circular economy requires intervention at different life cycle stages: product design (light-weighting, repairability, modular design), manufacturing (fabrication yield), use (longevity), and waste management (efficient recycling). While in the past the scientific literature has focused on waste management, our assessment shows a growing

[2] IPCC terminology for "below 1.5°C "(C1), "below 1.5°C with overshoot" (C2), and "below 2°C" (C3) scenarios.

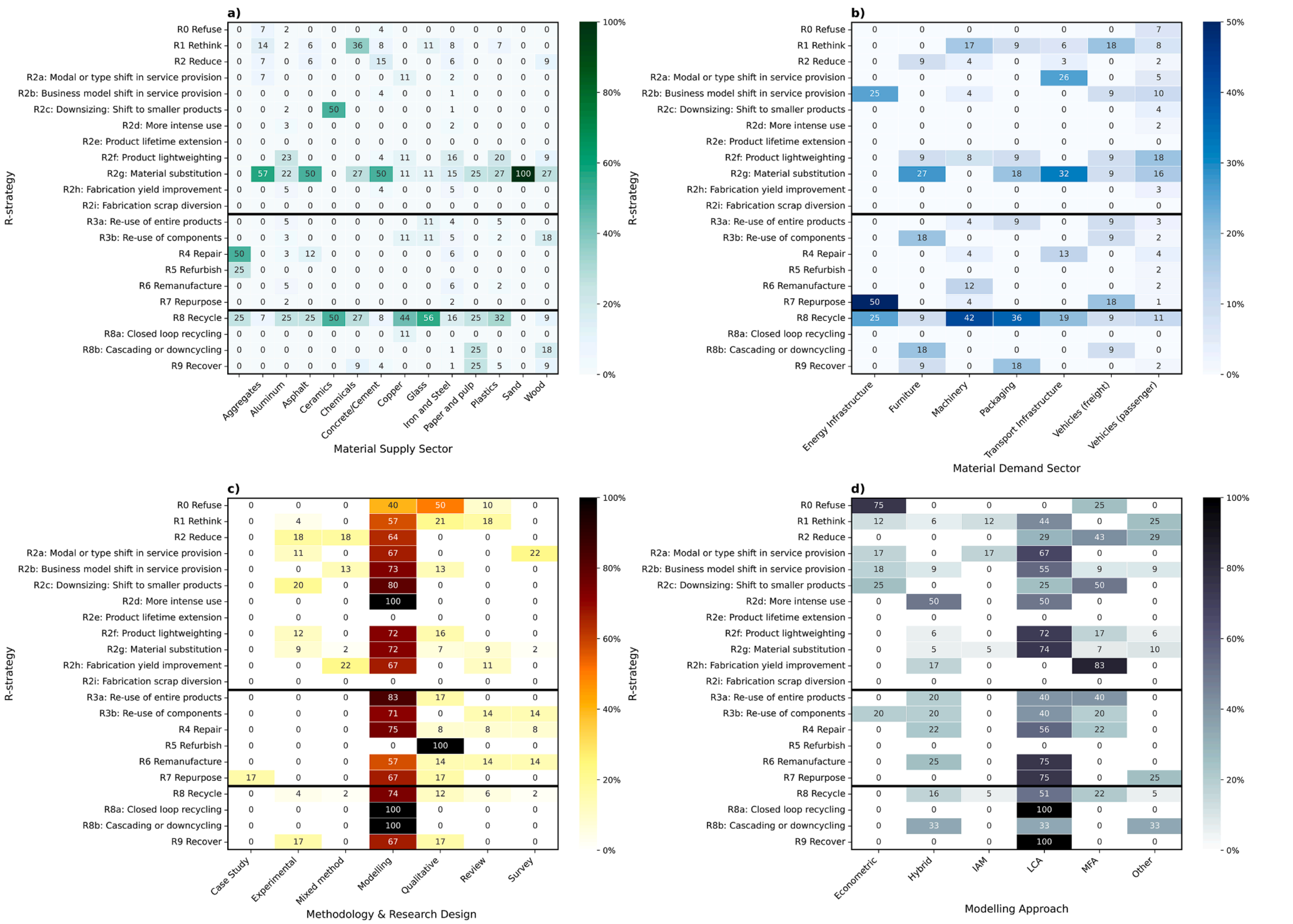

Fig. 3. Heatmap of R-strategies per material supply sector (a), material demand sector (b) per methodology and research design (c) and modelling approach (d) in the assessed literature. Results in a-b are normalised by columns; in c-d they are normalised by rows.

importance of interventions in product design, manufacturing, and use. Studies have emphasised the importance of reducing overdesign (i.e., "designing and developing products or services beyond what is required by the specifications and/or the requirements of the customer or the market (Ronen, 2008)) or optimising design to reduce resource use and efficiently provide material services (Hertwich et al., 2019). For instance, material use in typical building frames could be reduced by about 50% through early-stage design decisions, reducing embodied carbon by 40–60%, and costs by 10–20% (Dunant et al., 2018). Similarly, concrete structures are often beyond minimum standard requirements and it has been reported that cement use in structural elements could be reduced by 20% by changing the way elements are specified (Shanks et al., 2019). However, achieving such reductions in practice involves trade-offs with construction costs, productivity, and engineering effort, as producing structural elements closer to required specifications demands more precise design and quality control. These measures could nonetheless reduce resource use and related emissions without compromising service provision quality.

Design also affects lifetimes, material composition, performance, ease of transport, collection and assembly/disassembly, and potential for reusability and/or recyclability, therefore affecting the implementation potentials of each R-strategy. For example, short building lifetimes in some Asian countries can be attributed to the inadequacy and inflexibility of buildings built during rapid urbanisation and industrialisation (GlobalABC/IEA/UNEP Global Alliance for Buildings and Construction et al., 2020; Cai et al., 2015; Wang et al., 2018). Studies have investigated the potential benefits of extending building lifespans, which can reduce upstream energy demands. By extending the lifespan of Chinese buildings to 50 years, CO_2 emissions could be reduced by over 400 Mt per year, saving 3 EJ of energy annually (Cai et al., 2015). The question remains whether new buildings can be designed to meet evolving demands and avoid rapid obsolescence (Hong et al., 2016; Hu et al., 2010; Huang et al., 2013).

Design is particularly important in the plastic system. Because plastic recycling is predominantly mechanical, which often results in downcycling and degraded material performance (Hopewell et al., 2009), part of the CE strategy in this sector refers to the adoption of chemical recycling technologies (i.e., waste management) to break down waste plastics into basic chemicals and convert them into secondary feedstocks (Ragaert et al., 2017). However, upstream strategies to restructure the feedstock supply chain are especially significant because plastic production relies heavily on fossil-based feedstocks, with limited input from biomass (Zanon-Zotin et al., 2024; Jiang et al., 2024). Therefore, reducing fossil-based plastics production directly lowers the utilisation factor of oil refineries. A fundamental transformation at the production stage, integrating chemical manufacturing into the circular framework, can drive systemic changes across both energy and materials systems.

3.4. *Local and regional aspects of CE are key to understanding the net benefits to GHG mitigation*

Material use across countries has been driven by factors such as population growth (Krausmann et al., 2013), GDP (Steinberger et al., 2010), income (Schandl et al., 2018), prosperity, urbanisation (Schiller and Roscher, 2023), cultural, and geographical (Yi and Yang, 2014) aspects. The scale and quality of materials inputs, stocks, and outputs are therefore diverse at various spatial scales, leading to uneven distribution of material services provision and scrap/waste generation (Pauliuk et al., 2013) as well as material extraction and processing activities and their related socio-environmental impacts (Ali et al., 2017). CE strategies should not exacerbate but alleviate these disparities towards climate, energy and materials equity. This involves the use of local material alternatives (Casarejos et al., 2018) to avoid transportation emissions (Coloma-Jimenez et al., 2022). Industries can also leverage from recyclable and reusable waste – such as metals, plastics, paper, and glass – by trading them from regions where primary consumption has reached saturation to those in the process of building stocks (Pauliuk and Müller, 2014). This can help avoid unnecessary primary material production. However, the nature of this trade varies widely from high-mass and low-value materials (e.g., construction and demolition waste) to low-mass and high-value waste streams (e.g., e-waste and critical materials).

Co-benefits or liabilities should be further investigated as international waste trade reportedly affects critical metal transfers across borders (Cai et al., 2023) and involves environmental issues (Brooks et al., 2018). International trade may also influence and be influenced by low-carbon dynamics as manufacturing plants may relocate depending of regional comparative advantages for low-carbon production, redefining global value chains (de Sa and Korinek, 2021).

4. Current CE modelling practices for materials and GHG mitigation

This section provides an overview of the most common modelling approaches used to quantify the impact of CE measures on GHG emissions, distinguishing between IE models, which capture material stocks and/or flows and macro-scale models used for climate change mitigation, which simulate either energy or economic system transformations. Together, these modelling families represent complementary perspectives: one focused on material circularity and resource use, another on energy flows and decarbonisation, and a third on macroeconomic dynamics, all essential for quantifying the interlinkages between CE strategies and climate change mitigation.

IE models, particularly MFA, provide the foundation for evaluating circularity from a material-centric perspective. It explicitly traces the stocks and flows of materials across systems, enabling the identification of inefficiencies and circularity potentials. LCA and IO also contribute to IE research, with LCA evaluating material and environmental impacts at the product or process level, and IO capturing economy-wide interlinkages and footprint effects that extend across sectors. However, despite their respective strengths in evaluating circularity measures and their effects, including on GHG emissions, LCA and IO lack an explicit stock–flow representation, and more broadly, IE models have limited capacity to integrate technological evolution and macroeconomic dynamics, both essential for assessing circular economy contributions to climate change mitigation.

Conversely, climate change mitigation models, namely process-based IAMs or Energy System Models (ESMs), are specifically designed to evaluate energy system changes needed for reducing GHG emissions, having a detailed representation of energy and technological transitions. Macro-scale CGE models are usually used to capture the macroeconomic effects and provide a comprehensive view of prices linked to these energy system transformations. Yet these tools generally do not consider material-flow dynamics and stocks, which constrain their ability to represent circularity mechanisms.

Despite their differing analytical focuses, these modelling families are complementary: IE models may elucidate material and resource dynamics, whereas IAM/ESM capture systemic transitions within the energy, and CGEs represent the macro-level changes in the economy. Together, these approaches may provide a coherent framework for analysing how material, technological, and economic transformations interact within circular economy and mitigation strategies.

Complementary modelling approaches such as agent-based models (ABM) and system dynamics (SD), which address respectively, behavioural and feedback-loops around stocks and flows have also been applied to assess circular economy strategies (Walzberg et al., 2021). However, they are often applied at limited or simplified system scales (Walzberg et al., 2023; Guzzo et al., 2022), which limit their ability to provide economy-wide quantification of material flows and GHG outcomes.

A more detailed description of the modelling approaches, along with illustrative applications of materials inefficiency assessment and/or circular economy measures, is provided in Table 5, which presents a summary of models main characteristics, analytical strengths, and limitations.

4.1. Material flow analysis: stock-flow representation

MFA provides a quantitative assessment of specific physical material flows and their accumulation into stocks from extraction to end-of-life, making it a key tool for assessing future recycling potential, material cycles, and for informing circularity opportunities across the entire material cycle. Conventional static MFA has evolved into dynamic methods (Müller, 2006), enabling multi-year evaluations of material stocks and flows with variable product lifespans. It has been linked to additional methods such as the Weibull and lognormal distribution functions for lifetime modelling, Monte Carlo simulations to propagate uncertainties, logistic growth functions to represent stock saturation, and other stock-based mathematical modelling (Islam and Huda, 2019; Pauliuk and Heeren, 2020). By capturing the dynamics of in-use stocks, inflows, and outflows, MFA may support the development of biophysically feasible pathways for dematerialisation and decarbonisation (Wiedenhofer et al., 2019), making it a valuable tool for integrated analysis of stocks-flows-service nexus (Haberl et al., 2021). There is a vast literature using MFA models to evaluate circularity, covering many sectors, such as e-waste (Islam and Huda, 2019), plastics (Eriksen et al., 2020; Klotz et al., 2022), construction (Lederer et al., 2020), vehicles (Pauliuk et al., 2021), and exploring the effects of different CE strategies, particularly analysing the potential of R-strategies that require a consistent understanding of flows and stocks of materials, such as product lifetime extension and more intense use, recycling, material substitution, or manufacturing yield improvements (Reduce). Despite its strength, as LCA, MFA does not capture market mechanisms, business models, and an economy-wide economic balance, failing to capture rebound effects of changes in the material cycles (Zink and Geyer, 2017). Additionally, the absence of endogenous technological choices, addressed by the use of exogenous carbon intensities or energy patterns (e.g., (Pauliuk et al., 2021)), hinder MFA's ability to fully capture the broader systemic impacts of circular economy strategies on climate mitigation.

4.2. Life cycle assessment: environmental footprints of products, processes, and services

LCA is a standardised method (ISO 2006; ISO 2006) that systematically quantifies and evaluates the inputs, outputs, and potential environmental impacts of products, processes, services, or systems, through their entire value chain. This method is particularly relevant for product-level CE strategies, identifying which products or processes offer the best environmental benefits when transitioning to a circular economy, including the effects on global warming. Slowing and closing loops (reuse and recycling strategies, respectively) were found to be frequently assessed by LCA (e.g., (Cusenza et al., 2019; Niero and Olsen, 2016)), although modelling recycling faces challenges, particularly in quantifying material substitution and downgrading quality of secondary versus primary materials (Niero and Olsen, 2016; Haupt and Zschokke, 2017). Additionally, assessing shared and Product-Service Systems in LCA has limitations due to the challenge of defining a functional unit

Table 5
Summary of the main modelling approaches for CE and climate change mitigation.

	Modelling Approach	Focus	Strengths	Limitations in modelling circular economy–climate linkages
Industrial ecology	Material Flow Analysis (MFA)	Material stocks and flows in a system	- Tracks material use, waste, and inefficiencies at different scales (from city to global) - supports dynamic analysis (d-MFA) - Allows analysis from a service demand perspective. Enabling the study of circular strategies' effects over time, via capturing stock-flow dynamics	- Limited mitigation assessment – sustained by exogenous parameters (carbon and energy intensities) - Does not capture raw material scarcity - Does not cover economic mechanisms
	Life Cycle Assessment (LCA)	Material and Environmental impact of products/systems	- Standardised method - Broader view of environmental impacts besides GHG - Useful for CE strategies (reuse, recycling)	- Static, no material stock-flow dynamics - Difficult to model changes over time - Product/service-centred and not scalable to total consumption levels - Lacks economic mechanisms, although can cover costs
	Input-Output Analysis (IO)	Economy-wide assessment of changes in materials linked sectors (demand and/or supply)	- Captures full supply chain and macroeconomic effects. - Includes environmental extensions, enabling quantification of impact redistribution across sectors. - Identifies burden shifting and rebound effects of circular strategies. - Relatively accessible global data, supported by established databases (EXIOBASE, WIOD, EORA). - Allows rapid exploration of circular economy potentials through what-if scenario modelling on the global supply chain - global footprint perspective	- High sectoral/product aggregation; lacks process-level resolution; assumes sectoral homogeneity. - Based on monetary flows, which may distort physical or carbon flow representations. - Limited capacity to represent specific circular strategies (e.g., remanufacturing). - Time series available but no stock-flow dynamics - Mostly monetary units only
Computable General Equilibrium (CGE)		Economy-wide policy impact analysis	- Global economic system coverage (providing macro-economic indicators – e.g., employment) - Rebound effects are accounted - Covers market potential of circular economy linked to substitution elasticities – based on historical data	- Absence of high technological detail - Most CGEs are recursive but, while challenging, they can be made dynamic - Lower granularity of sectors/products compared to IAM, ESM, or MFA - Do not represent innovation breakthroughs (new types of goods and services) - recursive structure restricts dynamic investment and forward-looking decisions.
Process-based IAMs/ESMs		Energy system transformation (technology profiles) for climate mitigation	- Detailed and explicit representation of technology stocks and energy carrier flows - Dynamic assessment of the energy system - Possible optimisation – cost-effectiveness - Include other GHG, e.g., land-use emissions (not included in ESM) - Scenario-based analysis including policy levers (carbon price, technology mandates, etc.)	- Lacks endogenous material flows - Limited representation of macroeconomic feedback - Often lacks detailed behavioural dynamics - Simplified representation of global supply chains
Agent Based Modelling		Behavioural interactions and decision-making of agents	- Represents behavioural heterogeneity and interactions between agents, capturing social influence and policy incentives - Allows exploring the adoption of circular practices and new business models	- Usually applied at local or sector-specific scales; scaling to national or global levels is computationally demanding due to high data and calibration requirements - Material flows and GHG emissions are often simplified or exogenously parameterised - Validation and reproducibility can be challenging due to complexity and context-specific assumptions.
Systems Dynamics		Feedback loops and dynamic interactions between stocks and flows	- Captures feedback mechanisms, delays, and non-linear dynamics, - allowing to represent the interactions between resource use and GHG emissions. - Suitable for analysing how circular strategies interact with climate policies and lock-in effects.	- Relies on aggregated or stylised representations of material stocks and flows - Emissions often represented through simplified coefficients - Limited empirical calibration at economy-wide scales and reduced comparability across studies

(Amaya et al., 2014; Kjaer et al., 2016; Martin et al., 2019). The static nature of LCA also limits its ability to analyse dynamic and integrated systems, such as evolving mobility patterns or climate mitigation strategies (Walzberg et al., 2021).

4.3. Input-output analysis: intersectoral economic flow accounting framework

IO enables economy-wide assessments of changes in material-related demand or supply, capturing full supply chain effects and macroeconomic consequences. It has evolved into hybrid forms, including physical coefficients and Environmentally Extended IO (EEIO), helping to identify burden shifting and rebound effects of circular strategies. Grounded in national accounts, IO avoids system boundary issues by covering all declared monetary flows (Aguilar-Hernandez et al., 2018). IO also benefits from comprehensive global databases (EXIOBASE (Stadler et al., 2018), WIOD (Timmer et al., 2015), EORA (Eora Global MRIO 2025)), supporting large-scale applications and allowing the understanding of the spillover effects of circularity between countries (Aguilar-Hernandez et al., 2018; Tukker et al., 2016). However, structural limitations persist: high aggregation, sectoral homogeneity assumptions, and lack of process-level detail hinder the explicit modelling of strategies like remanufacturing. Its monetary basis may distort physical or carbon flow estimates. In the circular economy context, Aguilar-Hernandez et al. (2018) (Aguilar-Hernandez et al., 2018) reviewed prevailing EEIO applications modelling approaches, classifying the circular interventions into four main categories: residual waste management (RWM), closing supply chains (CSC), product lifetime extension (PLE), and resource efficiency (RE). Modelling these strategies involves a "what if" scenario approach, adjusting waste inputs (RWM), IO coefficients (CSC), demand and input structures (PLE), or input intensity (RE). However, most EEIO models use monetary units, which mismatch physical-unit policy goals, especially for RWM. Waste IO models, as developed by Nakamura and Kondo (2009) (Nakamura and Kondo, 2009), are relevant in the context of circular economy by quantifying system-wide effects of alternative waste management options

4.4. Computable general equilibrium models: multi-sector equilibrium with price adjustments

CGE models combine general equilibrium theory with realistic economic data to describe the allocation of resources as the result of the supply and demand behaviour that leads to market clearing conditions (e.g., capital, labour, materials) (Wing, 2004). They have gained widespread use in assessing the effects of (fiscal) policies and economic shocks, particularly in the context of climate mitigation. In recent years, there has been a growing body of literature dedicated to expanding and adjusting CGE models to better capture the complexity of circular strategies and policies. They have been employed to explore the economy-wide impacts of price changes due to the increase in resource efficiency (e.g., (Ross et al., 2023)), the existence of repairing sectors and products (e.g., (Brusselaers et al., 2022; Peng et al., 2019)) or the inclusion of secondary/recycling products manufacturing (e.g., (Nechifor et al., 2020; Winning et al., 2017)). These models incorporate behavioural responses by maximizing consumer utility and producer profits (Boonman et al., 2023), and can account for substitution effects across products, sectors, and regions, making them valuable for evaluating rebound effects and trade-offs in circularity (Aguilar-Hernandez et al., 2021). Nonetheless, like IO, standard CGE models are more aggregated compared to bottom-up models like IE models that provide greater detail by focusing on specific sectors and products and do not capture physical flows, limiting their ability to analyse circular economy dynamics (Winning et al., 2017).

4.5. Integrated assessment/energy system models: technology-rich energy transformation modelling

Process-based IAMs and ESM have been central to climate mitigation assessments, providing a technology-rich perspective on how energy must evolve to meet specific mitigation targets, with IAMs extending the scope to include coupled land-use interactions. Although these models link technology stocks to energy supply and demand, and offer a high detail on bulk materials manufacturing (e.g., iron and steel, cement) and energy-related products (e.g., vehicles), they lack a physical connection between technology stocks and the materials required for them (e.g., iron and steel necessary for vehicles). This absence of material cycle blocks a comprehensive assessment of CE and the role of bulk materials demand in climate change mitigation. Recent efforts have been trying to address this gap, focusing on quantifying bulk materials use associated with climate change mitigation pathways via post-processing analysis (Deetman et al., 2018; Deetman et al., 2020), soft-linking IAM and ESM with material flow modules (IRP 2024) or to a lower extent, by integrating the connection between energy technology stocks and materials needs (e.g., for cobalt (Seck et al., 2022), lithium (Hache et al., 2019), plastics (Stegmann et al., 2022)). Moreover, while most IAM/ESM do not explicitly represent waste flows, recent advances have been made, with Andreou et al. (2022) identifying waste management as the most frequently represented circular economy strategy in such models (Andreou et al., 2022), as shown by the work of (Kullmann et al., 2022) and (Stegmann et al., 2022). Despite these first steps, the endogenous accounting of material flows in IAM/ESM are still lacking in the literature (Schulze et al., 2024), making these models overlook the relevance of material efficiency to climate change mitigation (Pauliuk et al., 2017; Schulze et al., 2024).

4.6. Other CE modelling approaches

Literature has also identified other CE assessment methods that may be applied to climate mitigation. Guzzo et al. (2022), for instance, noted an increasing number of studies using SD to analyse the effects of various circular economy strategies, supply chain integration, and barriers, including policy issues (Guzzo et al., 2022). SD provides a detailed but narrow focus, suitable for examining CE at the microscale (process level) but challenging to apply at the meso- or macroscale (Walzberg et al., 2021), which are necessary to understand the relevance of CE for global and national climate mitigation. Given the significance of economic agents' behaviour in CE, ABM has also been used to examine how individual decisions affect systems such as energy infrastructure (Schlüter et al., 2021), supply chains (Arvitrida et al., 2016), waste management (Luo et al., 2019; Tong et al., 2018), environment-migration dynamics (Hansen et al., 2019), and new business models (Lange et al., 2021; Raihanian Mashhadi et al., 2019). Despite ABMs’ strengths in representing heterogeneity and spatial effects, they also present several limitations, including the need for extensive validation, large and detailed input datasets, high model complexity, and a level of abstraction that often restricts their applicability to specific case studies (Schlüter et al., 2021; Khan and Abonyi, 2022).

4.7. Existing combined modelling approaches

Recent research has increasingly explored *soft* and *hard* model-linking approaches and integrated analytical frameworks to overcome the limitations of individual tools and to capture the interdependencies between materials, energy, and the economy in GHG mitigation assessments (Nikas et al., 2022). Examples include the coupling of MFAs with ESMs to quantify material requirements of low-carbon transitions (Deetman et al., 2018; Deetman et al., 2021); the integration of LCA with IAMs to estimate environmental trade-offs and cumulative impacts (Mendoza Beltran et al., 2020; Sacchi et al., 2022); and the merging of CGEs or IO models with technological bottom-up frameworks to represent macroeconomic feedbacks and cross-sectoral linkages (Fattahi et al., 2023; Böhringer and Rutherford, 2008). These hybrid configurations move beyond purely energy- or material-centric analyses.

LCA has frequently been coupled with other modelling frameworks, most often in a post-processing analysis, to quantify the environmental impacts of CE strategies or energy transitions. Van der Voet et al. (2019) employed MFA-based metal supply and demand scenarios as a basis for LCA (Van der Voet et al., 2019), while Zhong et al. (2021) linked a global dynamic MFA with LCA to project future material demand in buildings and the associated emissions (Van der Voet et al., 2019). Likewise, several studies have applied LCA to assess transition pathways developed by ESMs and IAMs (Sacchi et al., 2022; Ichisugi et al., 2019).

MFA has been used to provide physical information on materials and/or stocks to other models, such as IO (e.g., MaTrace model (Nakamura et al., 2014; Pauliuk et al., 2017)), to ESM and IAM providing a bottom-up assessment of materials demands (Deetman et al., 2018; Deetman et al., 2020; Deetman et al., 2021) or even to CGE providing newly built stocks, which are converted in value added, through empirical regression equations (Cao et al., 2019).

The integration of ESMs and multiregional input–output models (MRIOs), particularly through the Make and Use framework, is currently under active exploration to enhance the representation of intersectoral connections and broaden environmental assessments beyond climate change (Budzinski et al., 2023).

Combinations of more than two models also exist, as the integrated assessment method proposed by Meglin et al. (2022) that combines MFA and LCA with EEIO as the connecting element (Meglin et al., 2022). Wiprächtiger et al. (2023) also combined the three approaches LCA+EEIO+MFA (IE4CE approach) to assess the potential of circular economy strategies to mitigate environmental impact (Wiprächtiger et al., 2023) . They used an extended EEIO to identify sector hotspots considering sectoral GHG emissions from a production and consumption perspective, followed by a modular MFA/LCA approach to determine the most impactful processes and flows.

Sassanelli et al. (2019) and Walzberg et al. (2021) provide an additional view of combining methods under CE assessment, revealing that modelling approaches are frequently merged within their own domains (e.g., combination of different industrial ecology modelling tools), rather than fully integrating cross-disciplinary perspectives (Sassanelli et al., 2019; Walzberg et al., 2021) . This methodological fragmentation can limit the ability to capture system-wide trade-offs, feedback loops, and the effects of CE strategies on climate mitigation.

Thus, to advance CE modelling, further efforts are needed to develop integrated frameworks that not only link different analytical methods but also address their inherent regional and sectoral inconsistencies, boundary mismatches, and data integration challenges.

5. Synthesis and discussion

The synthesis of CE empirical evidence and modelling approaches reveals gaps that limit a comprehensive understanding of the CE contribution to GHG mitigation across the economy. Overall, the reviewed literature suggests that current assessments of CE contributions to GHG mitigation remain fragmented across strategies, sectors, and modelling approaches. Four major gaps emerge from the literature: (i) the limited representation of Refuse and value-retention processes i-e-., Reuse, Repair, Refurbish, Remanufacture, and Repurpose measures; (ii) the insufficient treatment of interactions between narrowing, slowing, and closing loops, limiting the robustness of mitigation estimates; (iii) the underrepresentation of rebound effects, spillovers, co-benefits, and behavioural dynamics; and (iv) the limited integration between modelling approaches used in CE and climate change mitigation research, partly due to inconsistencies in system boundaries and resolutions..

Addressing these limitations requires more integrated and interdisciplinary approaches capable of consistently representing interactions between material, energy, economic, technological, and behavioural systems. The following subsections discuss these challenges in detail, focusing first on the current coverage of CE strategies (5.1), their interactions (5.2), followed by modelling needs for integration (5.3), and, finally, the role of open science and collaboration (5.4).

5.1. Coverage of different CE strategies

The findings presented in Section 3 reveal an uneven coverage of CE measures across materials, end-use sectors, regions, and R-strategies, which partly reflects the data limitations and the modelling challenges presented in Section 4. The following subsections therefore discuss key knowledge gaps in representing R-strategies as well as their implication for modelling CE for GHG emissions reduction.

5.1.1. Lack of studies in R0 – refuse and the link to policy

While refuse measures rank first in the CE hierarchy, this type of strategy, which integrates sufficiency and alternative service provisioning modes, remains underexplored in the literature, with only 3% of the reviewed articles. Just a few studies discussed the potential of reducing travel demand, namely through teleworking (Ceurstemont, 2023), as well as reducing air travel by choosing closer destinations, e.g., for holidays (Cocolas et al., 2020; Jacobson et al., 2020; Gossling and Lyle, 2021). These studies seem to suggest that the “scope for voluntary positive behaviour change in the air travel context is limited” (Cohen et al., 2013), and even financial incentives such as a carbon tax do not necessarily lead to a noticeable reduction in air travel (Markham et al., 2018). Therefore, substantially reducing the number of flights may require a combination of a “change of norms, effective policy instruments and better alternatives to air travel” (Jacobson et al., 2020).

This illustrates how, in reality, refusing housing or transportation is fundamentally shaped by policy, governance, and socio-political dynamics rather than by individual consumer choice. The demand for new buildings and infrastructure is driven by population growth, urbanisation, and housing needs, and decisions on new buildings and infrastructure are ultimately political, influenced by stakeholder interests, lobbying, and public discourse. This means that implementing Refuse at scale requires structural policy interventions, such as land-use planning, zoning regulations, or infrastructure investment priorities, rather than relying on voluntary behavioural change only.

To support further modelling, one needs to acknowledge that refuse measures overlap conceptually with the Sufficiency literature, as highlighted by (Bocken et al., 2022; Marsh et al., 2022), or even Degrowth theory (Keyßer and Lenzen, 2021). However, while degrowth approaches explicitly target a shrinking of the economy to stay within planetary boundaries (Keyßer and Lenzen, 2021; Kallis et al., 2018), CE strategies primarily address resource efficiency and material circularity. Some CE strategies, particularly narrow and slow ones, may lead to reduced consumption of final goods in specific sectors, but this effect is within an 'a-growth' or growth-agnostic framework that does not explicitly target economic development (e.g., measured by GDP), focusing instead on environmental and economic policies independently of their effects on economic growth (Van Den Bergh and Kallis, 2012). For example, Marsh et al. (2022) emphasised the under-representation of sufficiency strategies in the CE literature, such as avoiding construction projects that do not add to social and individual well-being (Marsh et al., 2022). Literature on Decent Living Standards could also be used for quantifying possible service level reduction in Refuse strategies (Kikstra et al., 2021; Schlesier et al., 2024; Vélez-Henao et al., 2026).

Beyond empirical and data challenges, the limited quantification of Refuse strategies seems to reflect the core assumption of continuous economic growth based on the SSPs, which supports most long-term climate mitigation modelling (Buhaug and Vestby, 2019). Given that service demand is usually derived from these exogenous economic and demographic projections, service provision is implicitly assumed to expand over time. Representing Refuse strategies would therefore require either endogenous service demand saturation or reduction mechanisms, or the adoption of alternative socioeconomic narratives. Moreover, the growth trajectories of different sectors are also interdependent: housing demand affects transport infrastructure needs, which in turn shapes the scale and distribution of transportation across modes (Berrill et al., 2024). Policy on lower demand needs to take into account the inter-sectoral links between housing, non-residential building services, infrastructure, and transport. Modelling Refuse while accounting for these complex interactions can be challenging as it requires capturing cross-sectoral feedbacks that most current models treat independently or not at all.

5.1.2. Slowing loops strategies are less understood

Prolonging products’ lifespan reduces the frequency of new product purchases and therefore the energy and materials used for manufacturing (Wolfram et al., 2021; Hertwich et al., 2019; Pauliuk et al., 2021), with higher environmental benefits for energy-efficient and low-emissions products over inefficient ones (Glöser-Chahoud et al., 2021). However, there is a notable lack of research on GHG mitigation potentials of Reuse, Repair, Refurbish, Remanufacture, and Repurpose measures, also called Value-Retention Processes (VRPs) (IRP 2018). Altogether, these measures represented only 12% of the total. While lifetime extension has been a common topic (Budzinski et al., 2020; Ryan et al., 2020), the energy and materials inputs (e.g., spare parts, replacement components) required to extend products lifetime and retains their value in economy are less explored (Russell and Nasr, 2023), although recent advances point towards that direction (Von Köckritz et al., 2026). From a modelling perspective, value-retention processes require dynamic stock–flow representation to capture the temporal interdependencies between product lifetimes and material/-product flows. Without this, lifetime extension may be treated as a simple reduction in material demand due to delaying stock turnover, ignoring timing effects, performance trade-offs, and potential increase in material and energy demand associated with VRPs.

5.1.3. Material substitution trade-offs and synergies require integrated modelling and policy perspective

While material substitution is mentioned across all sectors for many services, representing 20% of the reviewed sample (c), understanding the effects of scaling up alternative materials in an integrated framework is yet to be understood. Lightweighting measures, for instance, reduce emissions from operational fuel use but may lead to an increase of substitution materials such as, aluminium (Winnett et al., 2017), or polymers (Khalil, 2017) and an associated increase in material-related GHG emissions. Notably, various studies highlight the increase in environmental impacts during the production of lightweight materials, especially carbon fibre materials (Kawajiri et al., 2020; Timmis et al., 2015; Delogu et al., 2017). Likewise, there are performance synergies and trade-offs to be accounted for as the choice of materials can also impact the energy efficiency and durability of a product, e.g., it was found that the use of natural fibres in wind turbine blades do not bring relevant climate benefits as it required an increased use of reinforcement materials (Liu et al., 2022). Moreover, the net effect of lightweighting and material substitution should not be assessed individually, but by taking into account recycling rates, as they influence the optimal design choices (Liu et al., 2022).

All of this calls for an integrated product and material life cycle approach in modelling and policy, where availability, costs, and energy requirements for materials production are equally represented within a common framework. Most of the studies that assessed material substitution apply an LCA approach (almost three-quarters of the reviewed literature); however, its general static nature does not allow for a time-explicit consideration of changing material composition and recycled material use to effectively explore the climate synergies and trade-offs of material substitution. In contrast and as identified in Section 4, IAMs endogenously determine energy carrier choices based on availability, extraction, processing, transformation, and transport costs, together with climate constraints. Yet, material choices are typically absent or highly simplified, limiting their ability of modelling mechanisms that could reduce material demand as also highlighted by (Bataille et al., 2021).

5.1.4. Underestimation of rebound effects, spillovers, and co-benefits of CE

Building on the energy efficiency literature (Sorrell et al., 2009), rebound effects of circularity – i.e., overall increase in resource consumption levels despite improved efficiency in material, or service – are mentioned across studies as potentially offsetting mitigation benefits (Zink and Geyer, 2017). Dedicated reviews have mapped the definitions, mechanisms, and research gaps of CE rebound effects across disciplines (Metic and Pigosso, 2022; Castro et al., 2022), yet these effects are rarely the core of the studies assessing CE for GHG mitigation, with a few exceptions (Makov and Font Vivanco, 2018; Ottelin et al., 2020; Skelton et al., 2020).

Beyond conventional price-mediated rebounds, CE and climate policies can trigger broader systemic effects through behavioural responses, technological spillovers, and structural economic adjustments (Hertwich, 2005). At the same time, circularity can also generate environmental (e.g., pollution reduction, minimised land-use changes), economic (e.g., job creation, cost savings, resource independence, reduced inequality), and health (e.g., improved air quality) effects, further reinforcing the need for analysing the broader implications of CE strategies on the sustainable development goals.

Studies generally report environmental improvements due to CE, alongside positive, or at least neutral, socio-economic outcomes (Fevereiro et al., 2025). However, despite increasing attention, the empirical quantification of CE rebound effects remains limited (Lowe et al., 2024). In fact, recent work has further mapped how CE rebound effects interact across business model, product life-cycle, and socio-economic dimensions in manufacturing systems (Ferrante et al., 2024); nevertheless measurement approaches at the scale required for climate modelling remains underdeveloped.

The limited incorporation of rebound and spillover effects in IAMs may therefore lead to an over (or under) estimation of the net mitigation potential of CE. IAMs/ESM often treat demand and efficiency improvements as exogenous inputs, limiting their ability to endogenously represent economy-wide responses. While CGEs can partially address price-mediated and behavioural rebounds, results are highly sensitive to structural assumptions, particularly substitution elasticities, which are often difficult to empirically validate. Moreover, their computational complexity often requires aggregated sectoral and regional representations, increasing the risk of aggregation bias and masking heterogeneous sectoral and regional effects (Fevereiro et al., 2025).

Modelling rebound effects more consistently would require (i) integrating price-responsive demand functions linked to material intensity changes, (ii) coupling material flow models with sectoral and regional detailed macroeconomic equilibrium frameworks to capture full reallocation effects, and (iii) incorporating behavioural parameters that reflect empirically observed consumption responses. Policies that address rebounds directly include those that cap demand, e.g. via speed limits, zoning regulations for housing, or a ban of short-haul flights.

5.1.5. Limited integration of behavioural dynamics

Despite growing recognition of consumers' roles in the CE, the behavioural dynamics underlying circular actions remain underexplored. Some studies have analysed consumer reaction to and preferences within CE (Boyer et al., 2021; Boyer et al., 2021; Wang et al., 2020) but there is a lack of comprehensive studies addressing consumer behaviour beyond recycling, particularly actions like refusing, reducing, or reusing materials (Allwood, 2014; Schöggl et al., 2020). Generally, in CE, the social aspect of sustainability is often overlooked and conceptually not well integrated (Mies and Gold, 2021; Ghisellini et al., 2016). This lack of behavioural insight extends to models and decision support tools, which are often grounded in rational choice paradigms (Constantino et al., 2021).

While a rational choice assumes perfect information and logical decision-making, empirical evidence shows that neglecting behavioural and structural factors can lead to both over- and underestimations of adoption rates and associated mitigation potential (Wiedenhofer et al., 2025; Safarzyńska et al., 2012; Pettifor et al., 2017). Rational choice models lack the consideration of bounded rationality, habit formation, loss aversion, and social status considerations (Safarzyńska, 2018). Social dynamics are particularly neglected, with insufficient attention paid to social norms, interactions, and the diversity of human behaviour (Wijermans et al., 2020; Nyborg et al., 2016; Farrow et al., 2017). For instance, the mismatch between passengers' intentions toward low-emission modes and their actions can, for example, be explained by the fear of losing autonomy and the high valuation of freedom (Silva Cruz and Katz-Gerro, 2016; Thomas et al., 2014). Since the wish for autonomy is deeply rooted, nudges and information campaigns can support modal shifts from private vehicles only to a limited extent; more comprehensive changes in public policies easing the use of public transport (through e.g. connectivity, a uniform ticketing system) as well as, incentives for public transport companies, could lead to further modal shifts (Silva Cruz and Katz-Gerro, 2016). Accordingly, structural changes are necessary since “there is only so much that individuals can do if sufficient opportunities for behaving sustainably do not exist” (Kaaronen and Strelkovskii, 2020). The physical (e.g., infrastructural) and social context determine the availability of alternatives, as well as their salience, namely accessibility and ease of adoption (Kaaronen and Strelkovskii, 2020).

Also, the model types discussed in this review suffer from limitations regarding the inclusion of behavioural dynamics and social aspects of circularity. For example, LCA may only consider user decision-making in some parts of a product's life cycle (Caspers et al., 2023), or assume disposal methods in its assessment that are not commonly available to users (Hicks, 2022). Yet, human behaviour significantly influences environmental outcomes in LCA, especially for products like vehicles, light bulbs, and textiles, where the use phase is critical strongly impacts environmental effects (Hicks, 2022). While there have been attempts to better capture lifestyle change in IAMs (van den Berg et al., 2022; van den Berg et al., 2022), they still lack sophistication in capturing lifestyle changes and their impacts (Andreou et al., 2022). The models' failure to capture heterogeneous responses of different consumer groups and the structural effects of lifestyle changes on the macro-economy further limits their utility (Andreou et al., 2022). Similarly, CGEs often rely on overly rational assumptions, ignoring well-documented behavioural anomalies (Yang and Heijungs, 2018). Even ABM, despite explicitly representing heterogeneous agents and their interactions, faces high data and validation requirements, parameter uncertainty, computational complexity, and limited generalisability; consequently, it is less widely used in CE assessments. All these shortcomings persist partly because human behaviour is complex and difficult to model (Constantino et al., 2021) leading researchers to rely on simplified assumptions, stylised behaviours (Hicks, 2022) or insufficient empirical data (Corona et al., 2019). As a result, current models often overlook key factors such as cultural norms, habits, institutional constraints, and socio-technical feedback that shape circular economy outcomes (Niero et al., 2021).

Approaches such as LCA, IAMs, and ESMs risk underestimating rebound effects and overlooking unintended consequences of circular economy initiatives (Niero et al., 2021). As a result, they may overstate the mitigation potential of purely technological or efficiency-driven strategies (Mies and Gold, 2021; Ghisellini et al., 2016). This narrow focus on technical and managerial aspects, while marginalizing social dimensions (Zavos et al., 2024), can lead to policies that fail to achieve their intended outcomes.

On one hand, empirical evidence shows that even when circular options are technically feasible, adoption is often constrained by behavioural inertia, institutional lock-ins, and cultural norms (Bruce and Spinardi, 2018; Cohen et al., 2013). For example, studies on air travel demonstrate that even strong financial incentives, such as carbon pricing, may have limited effects on behaviour change (Markham et al., 2018), while barriers like autonomy preferences and reliability concerns hinder the uptake of sustainable alternatives (Silva Cruz and Katz-Gerro, 2016; Thomas et al., 2014). Important feedbacks and barriers remain unaccounted for without integrating these behavioural and structural factors into assessment models.

Modelling efforts that incorporate behavioural insights have shown more optimistic scenarios – for instance, the early adoption of electric vehicles can accelerate when social dynamics are included (Pettifor et al., 2017). Aligning circular products and services with consumer needs, promoting repairable and user-friendly designs, and improving awareness about waste practices (e.g., e-waste disposal) can facilitate broader acceptance and adoption (Parajuly et al., 2020). Yet, the reliance on simplified behavioural assumptions in IAMs, CGEs, and LCAs rather than actual data (Corona et al., 2019) means that policies may not effectively address real-world implementation challenges, particularly regarding consumer adoption and social acceptance of circular economy initiatives. This suggests that current model results should be interpreted with caution and complemented with additional social science insights and behavioural analysis.

5.2. Interactions between CE strategies

As observed in Section 3 and 4, GHG mitigation potentials of different CE measures are often assessed in isolation. However, these potentials are not additive since CE strategies interact through the relationship between material stocks, flows, and the services they provide (Haberl et al., 2021). Also, climate strategies interact with CE strategies, creating mitigation-CE synergies and trade-offs. Understanding these interactions is important to (a) obtain realistic estimations of CE's contribution to global GHG mitigation and (b) to provide policy recommendations that take an integrated perspective and lead to economy-wide benefits instead of focussing on a single sector, material, or product. Below we summarise the main interactions between CE strategies – narrow, slow, and close – pointing out why an integrated approach is required.

5.2.1. Narrow-slow interactions

Narrow measures targeting product design (e.g., lightweighting, downsizing, material substitution; Table 4) directly influence the effectiveness of slow strategies (Reuse, Repair, Refurbish, Remanufacture) during the use phase. For example, designing lighter products (R2f) can reduce material input for manufacturing, but may inadvertently reduce structural integrity, shorten service lifetimes, or limit repairability and recyclability. Conversely, product design choices (narrow) can enable slowing loops, e.g., by incorporating modularity or standardised components, which facilitate easier disassembly, component reuse (R3b, slow), or affordable repair (R4). The extent to which product lifetimes can be extended through reuse (R3a, R3b), repair (R4), remanufacture (R6) and repurpose (R7) depends on the initial product quality and durability, both defined at the design stage.

In most existing models, narrow and slow strategies are parametrised independently, e.g., lightweighting is represented in MFAs through reductions in material intensities or energy/material efficiency improvements and slow by increasing average product lifetimes. To avoid inconsistencies, lifetime distributions could be endogenously defined as a function of design parameters, rather than treated as exogenous assumptions. Alternatively, a more diverse set of product archetypes specifying material composition, durability, and expected service life could be defined, ensuring consistency between design choices and stock–flow dynamics.

5.2.2. Slow-close interactions

Interactions between slow and close strategies are well documented. Slow strategies extend product service life – therefore delaying product retirement, and the availability of end-of-life products and materials. This has implications to: (1) second-hand product availability in secondary markets (R3a), (2) product component availability for component reuse (R3b), and (3) material availability for recycling (R8) or recovery (R9). Since recycling (R8) systems depend on steady availability of scrap, extending lifetimes without narrowing material demand can mean that virgin production remains necessary because sufficient scrap is not available (regionally). These interactions vary across products, sectors, and regions. For example, in rapidly growing economies with expanding building and vehicle stocks, slow strategies may mainly delay the availability of secondary materials, while in saturated markets, they may directly reduce recycling feedstock volumes and associated industry turnover.

Therefore, slow and close strategies cannot be modelled independently since their interaction defines both the timing and volume of secondary flows. To further improve the representation of these interactions, scrap quality classes could be tracked to enable modelling downcycling vs closed-loop recycling. This would also help endogenise the decision between reuse and remelting, which is usually exogenously defined via scenario.

5.2.3. Narrow-close interactions

Narrow strategies shape the quantity and quality of end-of-life materials available for closing loops. For example, refusing services and products (R0), increasing product intensity of use (R2d), and reducing material input per unit of product (R2f) lowers the potential scrap volumes available at end-of-life. Lightweight vehicles require less steel, but consequently generate less steel scrap for recycling, which may constrain secondary supply. Moreover, material substitution (R2g, e.g., composites replacing metals) can complicate recycling processes, reduce recovery rates, or increase separation costs. Conversely, narrow strategies that embed recyclability considerations – such as material labelling and single-material design – enhance the effectiveness of close strategies by improving material recovery yields and quality.

In short, narrow strategies lower the quantity of scrap available and can either enable or hinder closing loops, depending on whether design decisions support or undermine recycling system requirements. Improving the representation of these interactions include endogenizing the recycling economics (e.g., increased scrap price induced by lower scrap availability resulting from narrow, which in turn affects recycling revenues), improving the representation of product archetypes with alternative EoL pathways according to design, among others.

5.3. Multi-layer modelling for comprehensive and consistent depiction of CE-climate link

5.3.1. Scientific principles

An integrated view of the socio-economic, technological, and environmental outcomes is essential for a comprehensive evaluation of CE's contribution to GHG mitigation, necessitating the integration of modelling approaches with distinct but complementary characteristics. Three core principles must be followed to ensure the usefulness of model couplings for the CE:

Comprehensiveness: Because of the many interactions in the material cycles, accurate CE assessments need to capture the mitigation potentials of CE across relevant sectors, products, materials, and regions. To that end, modelling approaches must represent supply and demand circularity technologies and practices across multiple stages of supply chains. This requires a detailed representation of various materials, industries, and end-use sectors, covering also energy transformation and different socioeconomic conditions. (Sorrell et al., 2009; Metic and Pigosso, 2022) have already emphasised the need to improve industry detail in GHG mitigation models in order to capture cross-sectoral relationships and sector-specific mitigation measures.

Consistency: To obtain decision-relevant results, modellers must ensure the alignment of definitions, system boundaries, sectoral classifications, and datasets across modelling approaches. A foundational challenge lies in reconciling diverse modelling approaches. Currently, the approaches used in both CE and climate mitigation, i.e., LCA, IO, MFA, CGE and process-based IAM/ESM models, offer complementary but incompatible systems. For example, material and energy consistency must be established between MFAs and IAMs/ESM (Kullmann et al., 2021), while monetary and physical consistency is required when linking CGEs with MFA or IAM frameworks. Likewise, the aggregate material demand and production trajectories in IAMs must be consistent with the detailed product-level assumptions from MFA or LCA. Differences in sectoral granularity, geographic focus, and temporal resolution can also hinder integration. Establishing common definitions, boundary conditions, standardised protocols for model linking, and scenario development can reduce inconsistencies, improve reproducibility, and allow meaningful model coupling.

Robustness: To ensure sound analysis, modellers must capture uncertainties, feedbacks, and sensitivities as well as explore wide ranges of possible developments to identify strategies that remain effective under multiple plausible futures. This ensures that credible and policy-relevant conclusions can be drawn. To enhance robustness, conventional approaches can also be complemented with participatory methods (e.g., co-creation workshops, stakeholder-based scenario analysis) and behavioural modelling.

Uncertainties remain pervasive in modelling CE strategies, especially in product lifetime distributions, material composition, adoption rates and behavioural responses, as well as technology innovation dynamics. These uncertainties are magnified in underrepresented regions, where data on material use and CE practices is scarce. A broad scenario framework can help deal with these issues by exploring alternative socio-economic pathways, highlighting options that are likely to be effective under many circumstances, not just under ideal conditions.

5.3.2. Model couplings: consistency measures and data needs

Effective model integration that adopts these principles requires protocols that preserve the integrity of individual approaches but also promote interdisciplinary dialogue. A concerted effort to establish standardised definitions for CE strategies and to harmonise sectoral and regional disaggregation is thus imperative.

While energy use per country and sector is widely accessible to the climate modelling community through sources such as the World Energy Balances from the International Energy Agency (IEA) (IEA 2025), data on material use and production, product composition, and current stocks remain scarce or are scattered in multiple databases that lack consistency with each other. Centralising and standardising material-related datasets, akin to the IEA's approach to energy modelling, would benefit the community. Shared databases with harmonised data formats – such as the Industrial Ecology Data Commons (IEDC) (Pauliuk and Heeren, 2022) and the Integrated Assessment Modelling Consortium (IAMC) (IAMC 2024) enhanced with harmonised material indicators – can improve the compatibility across models. These resources would enable aligning global material flows, stocks, and energy use at high granularity for consistent scenario analysis and dynamic model coupling. Until a global initiative on comprehensive material statistics is established, these harmonised efforts are critical for advancing integrated and policy-relevant CE modelling.

Without this shared foundation, inconsistencies will persist, reducing comparability across results and therefore their policy relevance. As shown in Table 6, coupling models with complementary strengths – such as IAMs and MFA or CGE IO and LCA – can enhance coverage across macroeconomic, technological, and biophysical dimensions towards a comprehensive assessment of CE and the interplay of circularity, materials, and climate mitigation policies and measures. Agent-based and system dynamics models are not included in this comparison, as they are less widely applied to large-scale quantitative assessments of CE–climate interactions.

Performing model couplings according to the principles above enhances coverage and provides systematic answers to the research questions:

While IO, LCA, MFA, IAM, and CGE alone are suitable to answer research questions designed coherently with their representation of the economic, technological, and biophysical systems, the combination of their features through model coupling allows for answering more complex research questions. For instance, MFA-IAM coupling increases consistency between total material demand and sectoral material inflow by linking material stocks and flows to long-term energy demand and emissions. IAM-CGE coupling increases consistency by capturing macroeconomic implications of technological change. MFA-CGE coupling provides insights on rebound effects and spillovers given a certain CE policy. IAM-CGE-MFA coupling increases overall consistency by capturing technological, economic, and biophysical feedbacks across energy, material, and macroeconomic systems, enabling an integrated assessment of circular economy and climate change mitigation pathways.

Given the dynamic nature of these research questions, dMFA is a key modelling approach for future CE modelling for GHG reduction. By incorporating material-specific dynamics in GHG mitigation scenarios, future assessments can set targets for secondary production, recycling

Table 6
Comparison of modelling approaches widely applied in CE and climate mitigation analysis and their couplings across macroeconomic, technological and biophysical dimensions.

		Economic system representation	Technological development and systems integration representation	Biophysical flows and stocks representation	Typical classification system
Definition		Monetary flows across sectors are represented, often assuming proportional or equilibrium relationships	Technological change is endogenously represented and integrated across sectors over time	Mass and energy balances are respected, i.e., explicit stock/flow representation of energy and materials	
IE	IO	Yes (static, proportional, and without price adjustments)	No	Partial (when extended with biophysical data, e.g., Environmentally Extended IO)	ISIC Rev.4, CPA, EXIOBASE, WIOD, OECD ICIO
	MFA	No	No	Yes, stock-flow consistency over time is unique	UN IRP Global MFA, Eurostat EW-MFA, HS/SITC-based material categories
	LCA	No	No (static process representation only)	Yes	Ecoinvent, ILCD
IAM		Partial (represents energy-economy interactions but not full market equilibrium)	Yes	Partial (currently for energy and carbon flows mostly)	IPCC, UNFCCC, IEA sector structure
CGE		Yes	Limited (technology often stylised via production functions)	No (but can be extended with environmental satellite accounts)	GTAP, WIOD, OECD ICIO, EORA, ISIC Rev.3/4
Coupling	IE-IAM	Partial (IAMs capture some economic feedbacks, IE provides monetary flows without equilibrium)	Yes	Yes	-
	IAM-CGE	Yes	Yes (through IAM; CGE adds economic feedbacks)	Partial	-
	IE-CGE	Yes	No	Depends (if coupled with MFA → yes; if only EEIO → partial; if standard IO without extensions → no)	-
	IEA-IAM-CGE	Yes	Yes	Yes	-

rates, product lifetimes, as well as anticipate the transformation of industrial processes, including the phase-down of blast furnaces, and the reduction of energy and emissions intensities of material production, which could challenge the hard-to-abate narrative for heavy industries (Lund et al., 2023). Just as previous IAM work was instrumental, through the IPCC reports, in providing quantitative evidence for the scale and direction of global climate action required for temperature stabilisation and shaping key targets established in international climate agreements (e.g., the well-below 2 °C goal in the Paris Agreement at COP21, the nationally determined contributions, commitments to net-zero pathways formalised at COP26 (UNFCCC 2024), and transition away from fossil fuels and tripling renewable energy capacity by 2030 at COP28), the next phase of IPCC assessments must establish equally or more ambitious benchmarks for material and resource efficiency through CE.

5.4. Open science, capacity building, and knowledge sharing

Collaboration across data providers and modelling communities is critical to advancing CE to GHG mitigation research and exploring ambitious scenarios (McCollum et al., 2020). Given the diversity of modelling tools and disciplinary expertise, promoting dialogue between the industrial ecology, climate policy, and macroeconomic modelling communities is essential. This collaboration can be facilitated through common projects, interdisciplinary workshops, shared data platforms, topical sessions in conferences, and co-authored publications.

Increasing access to open and harmonised databases is equally important. As mentioned before, current data repositories for material stocks, flows, and recycling rates are fragmented, limiting their utility for integrated analysis. A concerted effort to consolidate and update these datasets – such as through international initiatives – can offer a basis for more comprehensive and consistent material modelling. Furthermore, developing cross-disciplinary expertise can help researchers to better merge different modelling strategies, facilitating this dialogue.

5.5. Policy levers in CE modelling

Based on the results of this review, several recommendations can be drawn for strengthening the integration of CE into climate policy and their representation within modelling frameworks.

Policy discussions on circular economy could move beyond a predominant focus on downstream recycling (R8) targets and place greater emphasis on upstream material efficiency measures at the design and manufacturing stage (R2). This includes extending eco-design approaches to incorporate recycled-content requirements, durability and repairability criteria, and material use and lightweighting standards for key product categories such as vehicles and construction materials. Recent policy initiatives, such as the European Union Ecodesign for Sustainable Products Regulation, already indicate a broader transition from energy-efficiency-focused regulation towards product life-cycle and material efficiency considerations. Integrating such measure into climate policy frameworks, including the next round of Nationally Determined Contributions (NDCs) by 2030 and in national industrial decarbonisation strategies, could help align CE policy objectives with long-term GHG mitigation targets.

Achieving substantial reductions in material demand and associated GHG emissions should also involve broader demand-side policies influencing patterns of service provision, infrastructure development, and consumption. Decision-making related to urban planning, housing density, infrastructure investment, and public transport and mobility systems is strongly interrelated and jointly shapes long-term material stocks, energy demand and emissions pathways. More integrated planning approaches should therefore help avoid long-term lock-ins associated with continuously increasing service demand while supporting reductions in both resources use and related GHG emissions. This also reinforces the importance of integrated modelling frameworks that can link bottom-up material demand with production and capture cross-sector interactions to support CE policymaking.

Climate policy instruments could also better account for material-related emissions alongside operational energy emissions. Existing carbon pricing schemes and industrial decarbonisation policies primarily focus on direct emissions, while embodied emissions associated with material production and consumption remain only partially addressed. Expanding the scope of these instruments and policies through approaches such as product-level carbon standards or complementary consumption-based accounting frameworks should strengthen incentives for material efficiency and circularity across supply chains. Such developments would require careful consideration of emissions accounting methodologies, and compatibility with existing international trade and climate governance, particularly regarding carbon market mechanisms under Article 6 of the Paris Agreement.

However, efficiency improvements and circularity measures alone may not guarantee absolute reductions in material use or GHG emissions if rebound effects offset part of the expected gains. CE policies should therefore be complemented by additional measures, such as resource taxes. Measures such as speed limits, zoning and urban planning policies affecting housing and mobility demand, and restrictions on short-haul flights where lower-carbon alternatives exist, should not induce higher material consumption in other sectors. To help secure the mitigation benefits associated with circularity strategies and reduce the risk of rebound effects, these policies need to be coordinated across sectors.

The review further highlights the importance of regionally differentiated CE strategies. Measures effective in saturated markets with stable material stocks may not be directly transferable to rapidly developing economies where infrastructure and building stocks continue to expand. International cooperation, finance mechanisms, and technology transfer initiatives should therefore play an important role in supporting context-specific CE pathways in the Global South, avoiding the direct transplantation of policy models developed for high-income economies.

Finally, advancing CE modelling for policy support should also benefit from stronger international coordination on material-related indicators and reporting practices. This could include supporting and expanding initiatives such as IEDC (Pauliuk and Heeren, 2022) and IAMC material indicators, encouraging national material flow reporting aligned with common classification system. More reliable and comparable data on material use, recycling, and embodied emissions would improve the calibration, validation, and consistency of models while strengthening the analytical basis for monitoring progress, evaluating policy effectiveness, and defining quantitative targets for material efficiency and circularity. Such efforts should also facilitate the incorporation of material efficiency considerations into future climate and industrial policy frameworks.

6. Conclusions

This study contributes to advancing the understanding of the CE-climate nexus in three main ways. First, by jointly analysing the empirical evidence of CE mitigation potential and the ability of quantitative models to represent it, this work can offer modellers a set of model improvements that are priorities. We organised these needs around three key areas: stock-flow-service nexus, systems integration, and economic dynamics, based on the mismatches between empirical knowledge and modelling ability. Second, by mapping the literature onto a harmonised narrow-slow-close R-strategy framework, with clear measures description, across material demand and supply sectors, this review provides a structured overview of where GHG mitigation potential of CE is robust and where knowledge gaps remain. Third, by comparing the strengths and limitations of IE, IAM/ESM, and macroeconomic modelling approaches, this work identifies concrete pathways for model coupling that can improve the representation of CE in climate change mitigation assessments.

The empirical review shows that CE can play a significant role in global GHG mitigation, particularly in material-intensive sectors, such as buildings and transport, complementing mitigation efforts that focus on decarbonising energy systems. Steel and cement, which account for 32% of the reviewed literature, show the largest mitigation potentials. This dominance reflects two features: the high embodied emissions per tonne of these materials, and the concentration of their demand in infrastructures, where multiple R-strategies, such as design optimisation, lifetime extension, and high-quality recycling, can be applied simultaneously and reinforce one another. Under ambitious CE pathways, the reviewed studies converge on the finding that cumulative demand for steel and cement in buildings could be halved by 2050, although the magnitude of this reduction is sensitive to assumptions, such as floor-area saturation, demolition rates, and the regional distribution of new construction. This sensitivity is itself a key message: empirical evidence shows that this mitigation potential is heterogeneous across strategies, materials, end-use sectors, and regions, resulting that it cannot be assessed without considering stock dynamics and the interactions between R-strategies and climate policy. Recycling remains the most studied strategy (21%), but upstream measures, (i.e., material substitution (20.5%), lightweighting, lifetime extension, and rethinking service provision (11%) are gaining attention driven by the recognition that downstream interventions cannot, on their own, deliver the demand reductions required by climate targets. Key gaps persist around Refuse, Slow measures (i.e., value-retention processes), and rebound effects, which are strongly shaped by behavioural and social dynamics and therefore remain difficult to quantify using current modelling approaches. Importantly, not all CE measures deliver clear GHG reductions: trade-offs have been identified in lightweight composite production, wood-for-concrete substitution, and rebound effects that may offset mitigation gains. The literature also shows a shift from waste management toward product design and use-phase interventions, and highlights that stock expansion in the Global South constrains strategies effective in saturated markets, underscoring the need for regionally differentiated assessments.

The modelling review shows that current analytical approaches struggle to capture the systemic nature of circularity, with many assessments considering CE measures in isolation, without fully accounting for interactions between material stocks, production processes, energy systems, and economic feedbacks. As a result, important dynamics of circularity and materials production/use, such as feedback loops, trade-offs with climate policy, and long-term system effects are often overlook. Addressing these limitations requires integrating CE strategies into climate modelling, by moving beyond a sole focus on energy flows and services towards an explicit representation of the stock-flow-service nexus. No single modelling approach is however sufficient to assess the contribution of CE to GHG mitigation in a comprehensive way. Industrial ecology methods capture material stocks, flows, and life cycle impacts but generally omit economic feedbacks and energy system dynamics, while climate and energy system models represent long-term emissions pathways but treat material demand and circular flows in an aggregated manner. Macroeconomic models address economy-wide impacts and rebound effects, yet have limited capacity to represent physical material constraints and detailed circularity mechanisms. As a result, integrated assessments must draw on the complementary strengths of these approaches, ensuring broad coverage of materials, sectors, and circular strategies, coherence in definitions, system boundaries and data, as well as an explicit treatment of uncertainty arising both from parameter values and from the choice of modelling framework itself.

There are three main limitations to this study. First, while the heterogeneity of system boundaries, functional units, and mitigation metrics allows for a broad and sector-specific overview of CE measures, it also limits the comparability of reported results across studies. Second, the reviewed literature was restricted to articles and reports published in English and explicitly referring to the circular economy framework. Third, the rapid expansion of the CE literature meant that achieving a fully systematic and exhaustive review was not possible due to the volume of articles to be reviewed. The breadth and growth of the field required prioritisation and screening decisions that may have led to the exclusion of some marginally relevant studies. As in other recent reviews facing similar constraints (Magalar et al., 2026; Wiedenhofer et al., 2025; Hertwich et al., 2019), this study relied on expert-guided selection, which may introduce a degree of author bias in the coverage and interpretation of the literature. We have sought to mitigate this by involving a large and interdisciplinary author team including both IE and IAM communities, and by structuring the analysis around a transparent R-strategy framework, but acknowledge that alternative selections could yield different emphases. Moreover, the expert-guided selection applied in the modelling review (Section 4) and the snowball sampling in the empirical review (Section 3) limit the reproducibility of the selection process. Although we document search strategies, selection criteria, and the full list of reviewed articles in the Supplementary Table 1, we acknowledge that alternative selections could yield different emphases. Despite these limitations, the integration of empirical and modelling perspectives, and the involvement of both Industrial Ecology and IAM communities provide a robust assessment of the role of CE for climate change mitigation and for improving their representation within current modelling frameworks.

Section 5.5 translates these findings into policy recommendations, highlighting the need to broaden CE policy beyond recycling targets toward upstream material efficiency and demand-side measures, to incorporate embodied emissions into climate policy instruments, to develop regionally differentiated strategies, and to strengthen international coordination on material-related data and reporting. This review complements recent related work on CE-climate nexus (Hertwich et al., Dec. 2019; Magalar et al., 2026; Wiedenhofer et al., 2025). Across these, and despite the different scopes, there is broad agreement that CE mitigation potential is substantial but highly heterogeneous. All reviews find that 1) recycling and waste management dominate the literature over higher-priority strategies such as refuse and reduce, although this trend has been slowly shifting, 2) potential trade-offs and synergies exist between energy- and material-related mitigation measures, and 3) most studies rely on attributional LCA at the product level, with very few economy-wide assessments and studies that consider rebound effects. Our contribution extends this body of work by jointly mapping empirical evidence and modelling capability across all major sectors using a harmonised R-strategy framework, and by identifying where modelling capability has not kept pace with empirical knowledge.

7. Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT to improve the clarity and readability of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Marianne Zanon-Zotin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Patricia Fortes:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Darius Corbier:** Writing – review & editing. **Sebastiaan Deetman:** Writing – original draft, Methodology, Data curation. **Oreane Edelenbosch:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Martijn van Engelenburg:** Writing – review & editing, Writing – original draft, Data curation. **Christian Hauenstein:** Writing – review & editing, Methodology, Data curation. **Edgar Hertwich:** Writing – review & editing. **Meng Jiang:** Writing – review & editing, Writing – original draft, Data curation. **Luja von Köckritz:** Writing – original draft, Data curation. **Leticia Magalar:** Writing – review & editing, Writing – original draft, Data curation. **Stefan Pauliuk:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Lucas Straub:** Writing – original draft, Methodology. **Johan Vélez-Henao:** Writing – review & editing, Data curation. **Detlef van Vuuren:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.109053.

Data availability

Data will be made available on request.

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