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REVIEW

Thematic exploration of sectoral and cross-cutting challenges to circular economy implementation

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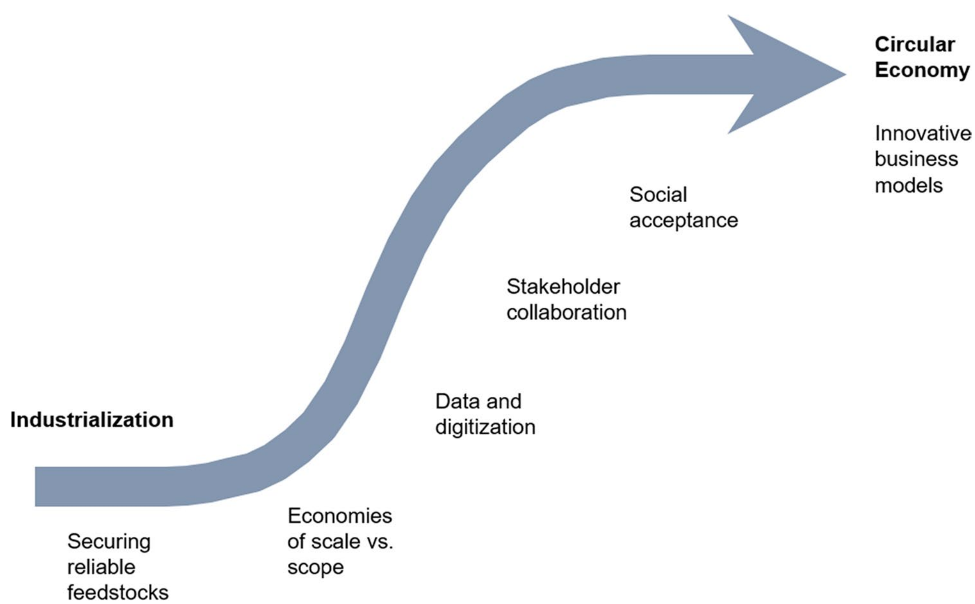
Abstract
Circular economy (CE) offers a pathway towards sustainable, closed-loop resource systems, but widespread adoption across industrial sectors is limited by fragmented knowledge and varied implementation approaches. This article reviews sector-specific challenges and opportunities associated with implementing and measuring the benefits of CE strategies. Literature mapping highlights progress towards CE implementation in food, chemicals, metals, consumer electronics, and building and infrastructure sectors, and towards measuring CE outcomes via systems analysis methods like life cycle assessment (LCA) and material flow analysis (MFA). However, key challenges were also identified that point to future research and demonstration needs. First, research on CE adoption typically exists as case studies that are closely linked to a sector. But literature has not effectively synthesized knowledge gained across domains, particularly understanding underlying barriers to CE and where they occur in product life cycles. Second, research on CE outcomes often applies well-established methods without adapting for unique attributes of CE systems. A key opportunity is in integrative methodological advances, such as expanded use of consequential LCA, development of physical Input–Output tables, and integrating MFA with dynamical models. Finally, regardless of sector, new CE business models are seen as a critical enabler to realize success, but theoretical frameworks in literature are not well-tested in practice. The review also highlights opportunities to harness other emerging trends, such as big data, to provide better information for system modelers and decision-oriented insight to guide CE stakeholders.

Graphic abstract



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Introduction and approach

Circular economy (CE) has gained widespread momentum as a means to achieve sustainable economic growth that is decoupled from resource extraction and waste generation. Recent years have seen a significant increase in research to develop and evaluate CE strategies (Kalmykova et al. 2018), in parallel to concurrent growth of new business models that seek to apply these strategies in practice. This confluence of interest in the CE paradigm has created unique opportunities for initiatives that engage diverse actors, including businesses, policy makers, and the academic community (Ghisellini et al. 2016). A recent article highlighted the importance of using lessons learned from CE application to establish priorities for future research (Babbitt et al. 2018). Given this motivation, the 2018 International Symposium on Sustainable Systems and Technology (ISSST), the longest-run interdisciplinary conference focused on sustainability science and engineering, held a special session on CE that brought together researchers and practitioners from industry, state and federal government, academia, community organizations, and national labs to explore how various groups were approaching this challenge. In 2019, the CE session coordinators organized a special issue on "Advances in the Circular Economy," which sought to understand the progress with which CE concepts were being translated into policy, business models, and industrial innovations (Singh et al. 2019).

This contribution aims to provide a perspective on what was learned from these collective efforts within the context of broader CE literature by focusing on sector-specific challenges as well as cross-cutting themes. Recent reviews of CE adoption have established challenges faced in specific sectors, such as manufacturing (Acerbi and Taisch 2020); business (Centobelli et al. 2020); construction (Osobajo et al. 2020) and waste electric and electronic equipment (Bressanelli et al. 2020), and proposed unification of circular economy research (Principato et al. 2019; Borrello et al. 2020). However, existing literature has not fully compared, contrasted, or integrated the lessons learned and challenges faced across sectors. Further, existing literature has not critically explored the gaps in existing methods for analyzing CE outcomes as it relates to these sectors. Therefore, the goal of this perspective article is to evaluate critical challenges and opportunities within key sectors and then assess the intersection of those opportunities as a means to prioritize future research and technology advancement. To this end, we first map available literature and identify points of convergence and distinction ("Literature review and mapping" section). Detailed sector-specific themes are explored in "Sector-specific themes" section followed by discussion of cross-cutting themes and enablers in "Cross-cutting themes" section . The key contribution of this work is in synthesizing the significant barriers and opportunities in implementing CE across sectors through a critical review of existing knowledge.

Literature review and mapping

Approach

Synthesis of literature to explore key CE themes was carried out in two parts. One part focused on a scoping analysis of the broad literature to understand core themes and trends, while the second part applied deeper analysis into key trends to investigate current challenges and opportunities. The broad literature review focused on CE implementation and application using search term *circular economy* appearing with related terms such as implementation, sector, application, case study, deployment, operation, or business. These terms were individually searched with *circular economy* using the Boolean Operator AND, and each of the above-mentioned terms were truncated to the root using the * operator to ensure all variants were included. Literature search was carried out in the Web of Science Core Collection for all years, resulting in approximately 3000 results. Title, author, keyword, abstracts, and references were downloaded and analyzed via keyword association using VOSviewer version 1.6.14. A thesaurus file was used to synchronize similar terms for consistency. For example, LCA, life-cycle assessment, and life cycle analysis were all recoded as *life cycle assessment*.

Identified themes were then critically reviewed by experts in each respective field (listed co-authors). Expert input was solicited from the ISSST special session participants and editors of and contributors to CE special issues. These topical literature reviews were structured and carried out to synthesize key challenges and opportunities relative to implementing CE strategies in identified industrial and business sectors and to evaluating CE outcomes using systems models. Finally, integration by way of thematic analysis was used to discuss common challenges and opportunities that were identified.

Identification of themes

The keyword association map generated for literature review on studies of CE implementation demonstrates four major

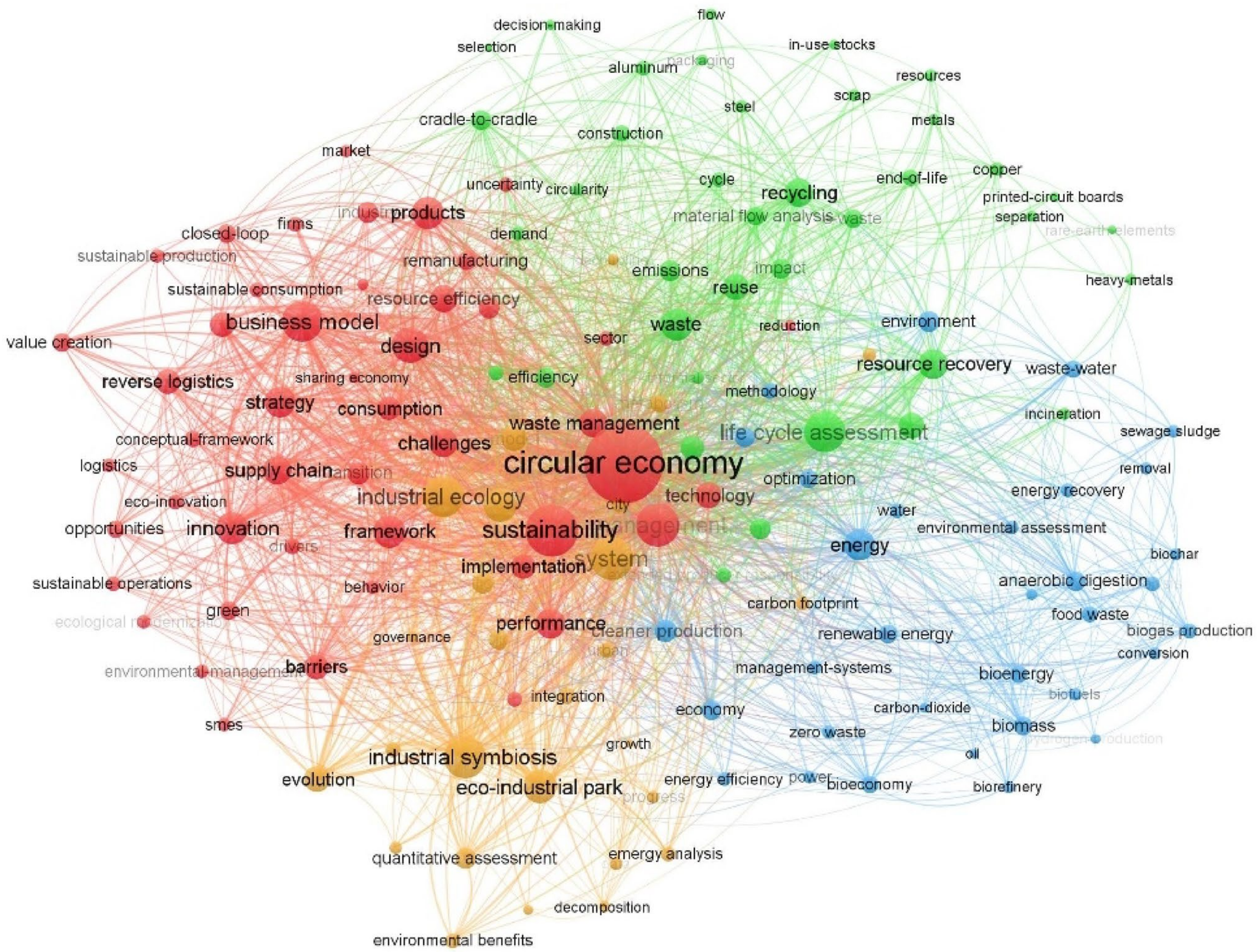

Fig. 1 Keyword association map for 3000 literature studies focused on circular economy implementation. A lack of cross-sectoral analysis in existing literature is shown by the lack of strong connections across themes. Major thematic groupings: Red: business models for circular economy; Yellow: Industrial ecology and symbiosis; Blue: food, bio-based, energy, and LCA; and Green: mineral, metal, and material flow analysis

literature clusters (Fig. 1). Studies applied to specific sectoral case studies are primarily shown as separate nodes on the outer regions of the blue and green clusters on the right of Fig. 1. There was a notable demarcation of studies that focused on topics such as metals, electronics, construction, and other infrastructure system (green) and that were commonly studied from the perspectives of cradle-to-cradle, material flow analysis (MFA), reuse, and recycling. Studies aimed at food, biomass, energy, and underlying chemical systems were clustered in the blue region and typically linked more closely with technologies aimed at recovering the energy contained in bio-based systems (through, e.g., anaerobic digestion) and carrying out holistic environmental analyses such as life cycle assessment (LCA). One observation from this high-level snapshot is that sector-specific studies were fairly fragmented, suggesting that research in this field has not fully undertaken cross-case comparisons or synthesis to identify commonalities and contrasts between challenges and opportunities for CE implementation for different sectors. Other approaches from the field of industrial ecology, such as input–output methodologies, are not very prominent in either sectoral space, suggesting a need for developing more connections between existing systems models and CE research.

The left regions of Fig. 1 (red and orange colors) are primarily focused on business and structural aspects of CE solutions. Industrial ecology as a whole was closely linked to circular economy, which is logical given the similarity in their conceptual bases and the overlap of assessment methods applied in each domain. Many industrial ecology-focused CE studies revolved around eco-industrial parks (EIPs) and industrial symbiosis from the business perspective. Given the close connection of industrial ecology to both the business node and to assessment methods like LCA, subsequent discussions will enfold that theme into respective analyses of these topics. Note that the strongest connections among business-focused research studies were amongst themselves (red region), with emphasis on new business models, innovation, supply chains, and reverse logistics. The keyword *framework* was central in this node, and many of the studies in this domain focused on establishing theoretical frameworks, but did not often carry through these approaches to the level of implementation in various sectors (note the absence of strong connections between the business domain and the sectoral studies on the far right). This analysis motivates our analysis of five key sectors (food and food waste, chemicals, metals and minerals, electronics and e-waste, and buildings and infrastructure) and four primary cross-cutting themes (data, models, stakeholder engagement, and business and innovation). Sector-specific thematic analyses are presented first, followed by cross-cutting thematic analysis. Since the approach is based on network analysis of existing literature for critical review, we anticipate that the network of existing literature and citations will change in coming years. This is especially applicable for CE as there is an exponential increase in publications related to CE. However, this analysis is envisioned to serve as a reference point against which progress in CE implementation can be assessed in the future.

Sector-specific themes

Key challenges and opportunities for implementing CE strategies in the five sectors discussed here are shown in Fig. 2. Each sectoral analysis includes a review of literature on CE strategies for the sector, followed by a discussion on key challenges and opportunities.

Food systems and food waste

Food systems have been a central part of CE studies for two reasons. First, they are critical to the well-being and economic vitality of a growing global population, and second, they face formidable challenges due to systems-level resource inefficiencies. Food supply chains consume significant energy and freshwater resources ((Pimentel et al. 2008; Canning et al. 2010; Maupin et al. 2010); release excess nutrient loads to vulnerable ecosystems; and contribute close

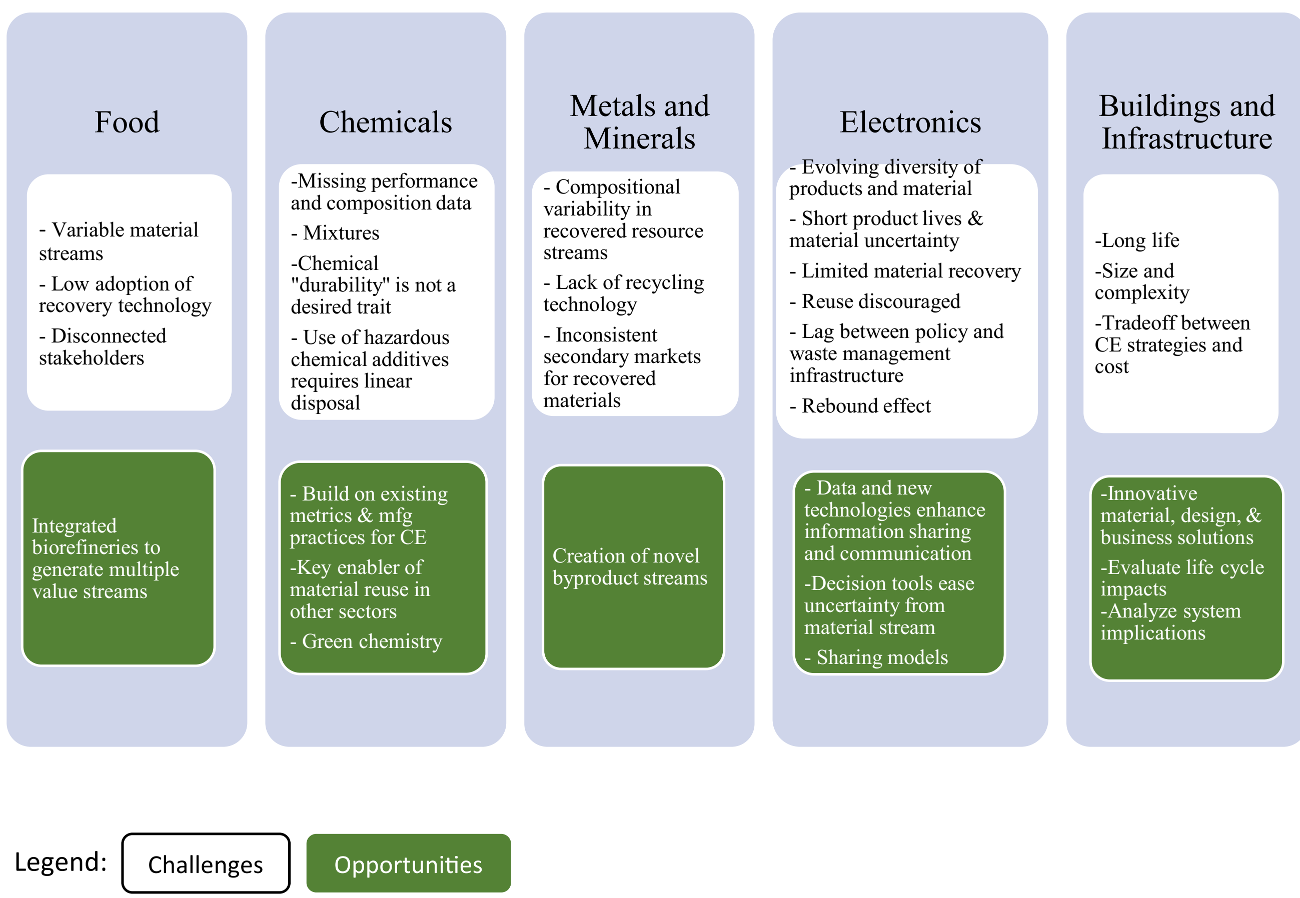

Fig. 2 Challenges and Opportunities for implementing CE Strategies in five sectors

to 15% of anthropogenic greenhouse gas releases (Pelletier et al. 2011; FAO 2013). However, 30–50% of food produced using these vast resources is never consumed, amounting to over 1.3 billion tons of food waste annually(Gustavsson et al. 2011). Food waste is typically disposed in landfills in many parts of the world, leading to further economic and environmental consequences, particularly climate impacts due to methane released as food waste degrades in landfills (Gunders 2012).

Food supply chains are ripe for transformation through CE strategies that maximize use of energy, water, and nutrients and transform waste streams into biological and technical resources. A significant body of CE research on food focuses on closing the loop on food loss and waste, as guided by the food waste hierarchy (Principato et al. 2019) (Fig. 3), which presents strategies for minimizing losses, returning food losses and wastes to productive use, or converting wastes into value-added or lower-impact byproducts (EPA 2018). With the exception of donating excess but still usable food, circular food recovery is primarily characterized by open resource loops where organic waste is repurposed or valorized into a new resource outside the food supply chain.

Common examples of waste valorization in CE literature are anaerobic digestion, fermentation, or transesterification, which convert food waste into bio-natural gas, bio-alcohols, or bio-diesel respectively (see e.g., Ebner et al. 2016; Hegde et al. 2018; Holm-Nielsen et al. 2009; Kayode and Hart 2019; Maroušek et al. 2020). The primary environmental benefit of transforming food wastes into value-added products is the expected displacement of fossil fuel energy carriers, electricity generation, and synthetic fertilizers. This fossil fuel displacement, coupled with avoided landfilling and attendant methane releases, results in life cycle greenhouse gas benefits (Bernstad and Cour Jansen 2012; Ebner et al. 2018). However, recent studies on food recovery in the circular economy context demonstrate that these benefits may not be realized under alternative methodological choices, such as system boundary, functional unit, or allocation method (Oldfield et al. 2018; Olofsson and Börjesson 2018), suggesting a need to reexamine LCA methods applied to bio-based circular systems.

Realizing the environmental benefits of circular food systems also relies on significant commitment, coordination, and communication among disparate stakeholders. For example, in some regions, the business community has been hesitant to adopt circular strategies beyond traditional waste management (Leipold and Petit-Boix 2018) and may require a clearer understanding of the value proposition, such as reframing organic wastes as bio-based resources (Perey et al. 2018). Lack of decision-oriented data and inconsistencies in data collection methods (Xu et al. 2016) are also barriers for stakeholders such as governmental agencies and waste managers. Overcoming these barriers will require new business models, incentive structures (Borrello et al. 2017), innovative policy mechanisms, and multi-stakeholder collaboration (Halloran et al. 2014).

Such collaborations among stakeholders must be mirrored by physical linkages within food waste management infrastructure, comprised of material separation, collection, hauling, pre- and final treatment, and distribution of value-added by-products. This infrastructure must be resilient to variability in waste composition (Fisgativa et al. 2016) and temporal and spatial shifts in generation volume (Lebersorger and Schneider 2014; Armington et al. 2018). Given that organic waste generation far surpasses the capacity of existing treatment systems, CE research on economic and environmentally friendly technology siting and deployment is also critical. Siting organic waste recovery facilities requires optimization of often competing objectives, such as compliance to local regulations, minimizing transport of waste and byproducts, economic input from tipping fees, access to road and utility networks, public perceptions, and

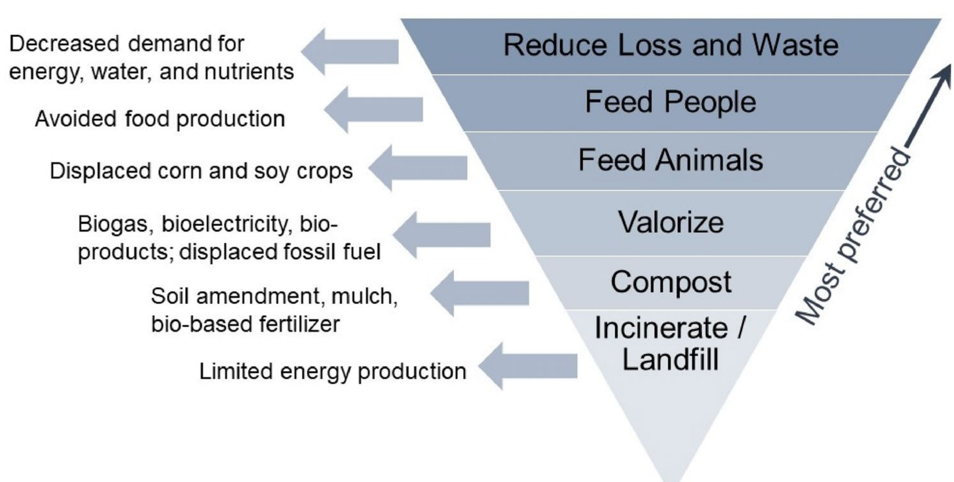

Fig. 3 Management of food losses and wastes by the U.S. EPA Food Recovery Hierarchy offers multiple pathway for closed-loop and open-loop circular economy strategies

avenues for managing residual solid or liquid wastes (Armington et al. 2018; Ma et al. 2005; Thompson et al. 2013).

Key barriers to implementing technology and infrastructure for circular food systems also include processing inefficiencies and lack of markets for utilizing the generated energy and byproducts (Nghiem et al. 2017; De Clercq et al. 2016). These barriers reflect the fragmented nature of food recovery processes, wherein technological solutions are aligned to specific waste streams, as opposed to a more fully integrated circular economy. These challenges also give rise to opportunity for innovation. A promising avenue is integration of organic waste-to-resource technologies, whereby food waste streams can be converted into a wide array of value-added byproducts by way of a "food waste biorefinery" (Armington et al. 2018). Like a conventional oil refinery, the incoming feedstocks (food waste instead of petroleum) are converted to multiple co-products, such as electrical or thermal energy, liquid fuels, fertilizers, soil amendments, specialty chemicals or solvent-grade alcohols (Hegde et al. 2018), which can make the operator more competitive, particularly during fluctuating demand for and prices of bio-products (Cherubini 2010; Lohrasbi et al. 2010; Maroušek et al. 2017).

Chemicals

CE implementation in the chemicals sector must be considered in two separate domains: pre-consumer, where chemicals firms have long been leaders in internal recovery and reuse of valuable feedstock materials; and post-consumer, where CE practices face significant challenges and recycling loops are essentially limited to certain plastics and textiles and minerals from non-hazardous industrial wastes (Garcia and Robertson 2017; Eckelman and Chertow 2009a, b; Haas et al. 2015). A recent material flow map for chemicals constructed (Levi and Cullen 2018) gives a holistic mass-based view of the chemicals value chain, totaling 820 million metric tons of chemical products entering use in 2013. In a report for the European Chemical Industry, it was estimated that up to 60% of these molecules could potentially be 're-circulated', through a combination of substitution, direct reuse of products or molecules, and recycling of molecules with re-synthesis into useful chemical products.

On the pre-consumer side, CE practices have been in place as long as the modern chemical factory has existed. One of the early titans of industrial chemicals production August Wilhelm von Hoffman (1848) said, "in an ideal chemical factory there is, strictly speaking, no waste but only products. The better a real factory makes use of its waste, the closer it gets to its ideal, the bigger is the profit'' (Cucciniello and Cespi 2018). In practice, chemical conversion processes are not ideal and give rise to co-products or by-products through primary or side reactions, as well as unreacted reagents, spent catalysts, and solvents. Large-scale integrated biochemical and petrochemical plants capture these streams through separation processes such as air stripping or distillation, conduct further purification or regeneration as necessary, and reuse them on-site or sell to partners (de Jong and Jungmeier 2015; Jenck et al. 2004). In very large chemical installations, chemical companies can run synthesis processes with linked value chains, so that byproducts from one process are used directly in another, what the German chemical giant BASF calls the *Verbund* concept.

One of the most active areas of research on pre-consumer CE practices is chemical process development for upgrading or valorization of byproducts from outside the chemicals industry (Cucciniello et al. 2016; Ricciardi et al. 2018), including through participation in eco-industrial parks or industrial symbioses where byproducts are exchanged among firms for mutual economic and environmental benefit Guo et al. (2016). As emphasized by Kalmykova et al. (2018), the chemicals industry is uniquely positioned to enable circular economy practices by using chemical engineering innovations to enable reuse of resources from a range of large-volume waste streams. Examples include chemical processes for recovery of valuable metals from e-waste and metallurgical wastes and recovery of nutrients from wastewater treatment (BASF 2018; DOW 2019). This key role for the chemicals industry has been emphasized in research (Clark et al. 2016; Keijer et al. 2019), market studies (Elser and Ulbrich 2017), and industry documents c.f. from BASF (2018), Dow (2019) and the European Chemical Industry Council (CEFIC 2018). Chemical process innovation may enable greater circularity for resource streams that are currently underutilized, including lignin from pulp and paper operations that could in theory be used as a feedstock for a wide variety of aromatic molecules (Clark et al. 2016). Carbon dioxide has been cited by many as the 'holy grail' of potential byproduct feedstocks, sourced both from within the chemicals industry, which produces net 137 million metric tons annually (Clark et al. 2016), as well as from other industrial sources.

On the post-consumer side, the most important barrier to CE practices is chemical contamination and associated end-of-life safety concerns. In many cases chemical contaminants are added by design, such as flame retardants in plastics, Leslie et al. (2016) that enhance product performance but inhibit downstream recycling. Chemists, therefore, have a crucial role in promoting circular economy by redesigning polymers and other chemical products to achieve the same desired function without using inherently hazardous or inhibitory substances (Clark et al. 2016). CEFIC and the International Chemical Secretariat (ChemSec; ChemSec Report, Accessed 2020) also emphasize the importance of safety for the circular economy and the need for eliminating hazardous chemicals from the value chains, especially if the products are to be recycled and reused.

Chemical firms have also been active developers and adopters of metrics in both pre- and post-consumer domains, bolstered by popularization of design frameworks such as the Principles of Green Chemistry (Zimmerman et al. 2020). Measures such as *E*-factor or reaction mass efficiency (RME) focus on avoiding process wastes are aligned with circular economy goals. However, green chemistry principles also recognize that designing products to be long-lived or recyclable may not always be environmentally preferable, and include guidance for 'targeted durability, not immortality' and 'design for degradation', especially for bio-based materials (Mcdonough et al. 2003).

CE goals in the chemicals sector must not be naïve to other environmental considerations like energy use or toxicity and other chemical hazards. Contamination with toxic compounds has been a common reason why byproducts from the chemicals sector must be disposed of in controlled landfills, precluding their recycling or reuse (Geueke et al. 2018). Appropriate regulations have been applied to hazardous long-lived products when our understanding of toxicity has improved. For example, building products containing lead paint or asbestos should clearly not be targeted for circulation into new products. The same logic holds true for legacy chemicals that are highly persistent, bioaccumulative, or otherwise harmful to the environment, such as chlorofluorocarbon ozone depleting substances. Therefore, the pursuit of CE should balance the benefits of recovering chemicals and materials against the potential environmental or health damages of doing so, as is standard practice in LCA in order to avoid "burden-shifting", as noted in Sect. 4. CE practitioners should recognize that the most prudent course of action for byproducts or end-of-life products from the chemicals sector will sometimes be to pursue safe and secure disposal or thermal destruction, and focus their efforts instead on green chemistry approaches to design the next generation of products for recyclability.

Metals and minerals

The potential for the materials, minerals, and metals industries to move toward a circular economy is highlighted by the strong decline in resource intensity over the last 50 years (more production output with less inputs of material and energy resources; Worrell et al. 1997; Cleveland and Ruth 1998). Although economics are the main driver for this trend in these industries, literature points to opportunities to decouple resource extraction and economic growth (Behrens et al. 2007), a key foundation of a circular economy. However, as total consumption continues to rise and ore grades continue to decline, pressure increases for this sector. Literature focuses on opportunities for circular economy in the materials sector, including recycling (Singh and Ordoñez 2016), remanufacturing (Lieder and Rashid 2016a, b), enabling reuse via lifespan extension (Bakker et al. 2014), critical material mitigation (Gaustad et al. 2017), additive manufacturing (Giurco et al. 2014; Despeisse et al. 2017), and innovative product design and material selection (Bocken et al. 2016; Jawahir and Bradley 2016; Bradley et al. 2016).

One of the key challenges, however, is the translation of these practices from theoretical contexts to real production and manufacturing applications (Babbitt et al. 2018).

While recycling is one of the largest potential areas, and the materials sector can serve as a sink for end-of-life resources (Allwood 2014); recovery rates remain low for most materials. Even materials with robust collection and recycling infrastructure like copper, steel, and aluminum have recycling rates that hover around 50% while other key materials like glasses, plastics, rare earth metals, lithium etc. have rates under 10% and some with little to no recycling occurring. Key barriers here are material availability and compositional quality and uncertainty (Arowosola and Gaustad 2019). Collection of post-consumer materials and economic prevention of co-mingling remains problematic (Ferguson and Browne, 2001; Ferguson 2010). As products continue to integrate a wider diversity of smaller amounts of materials, dissipative losses of these materials will continue to increase without intervention (Zimmermann and Gößling-Reisemann 2013). On the compositional quality side, material mixing also causes tramp element accumulation in many material streams; this forces dilution and downcycling to meet compositional specifications of new products. The key needs here point toward a research roadmap that aims to better collect, identify, and sort materials in preparation for reuse, remanufacturing, and recycling.

Match-making across industries will also be critical to increasing utilization rates; industrial symbiosis has already occurred where co-location enables little to no transportation of these materials (Mathews and Tan 2011). Advances in data system are a key enabler here, as databases that can provide such match-making have been shown to be successful at promoting partnerships (Sun et al. 2017a, b; Herczeg et al. 2018). Other industrial ecology approaches are finding new applications in the material based circular economy, for example, electronic disassembly and shredding decisions (Ryen et al. 2018), waste management (Tisserant et al. 2017), mining and metals recovery (Corder et al. 2015), and resource efficiency goals (Ma et al. 2015). Literature also points to the importance of innovation in systems to recover industrial and manufacturing byproducts as resources in closed-loop systems. Slags, dross, coal combustion byproducts, mine tailings, red mud, and other materials formerly considered as "wastes" are being reexamined for resource recovery potential in addition to their use as additives in many applications (Liu and Li 2015; Qin et al. 2015; Hower et al. 2016; Lèbre et al. 2017). Like many other sectors, however, implementing these solutions will require concurrent investigation into mechanisms for engaging policy and industry stakeholders to enhance circularity (Hagelüken et al. 2016) .

Electronics and e-waste

The electronics sector has emerged as a common topic for materials-focused CE case studies, both in terms of enhancing loop-closing activities such as recycling and as a backdrop for analyzing specific materials, such as printed circuit boards, rare earth elements (REE) and other metals (Fig. 1). Initially comprised of a few single use, large devices, electronics have emerged as a vast ecosystem of mobile, smart, and connected devices (Internet of Things). This system continues to evolve as electronics are embedded in non-traditional products like jewelry, clothing, household appliances, toys, and health monitoring wearables for people and pets (Saner 2017; Bonato 2010; Association 2018; Ryen et al. 2014, 2018; CTA 2016). While CE has achieved success with recycling, products continue to be designed and produced for a linear system, material recovery is limited, and current systems/attitudes discourage reuse (Singh and Ordoñez 2016) .

Collectively, innovations in technology and design strategies play an influential role in CE strategies for the electronics sector. For example, enhancing strategies to eliminate toxic or emerging containments and integrate new, biodegradable, nontoxic materials (carbon and pyrene) have been identified as key opportunities to push the industry towards a zero-waste pathway (Bakhiyi et al. 2018; Fu et al. 2016; Li et al. 2015). Design strategies in literature focus on extending product lifespan and enabling reuse options through durability, elimination of high failure rate parts, preventing perceived or planned hardware obsolescence induced by the software, strengthening emotional connections with devices and enhancing modularity (Bocken et al. 2014; Wever 2012; Coughlan et al. 2018; Egenhoefer 2017; Komeijani et al. 2016; GEC 2018, p.8;). Standardized connectors (snaps rather than glue) and accessories (power cords) are seen as critical for enabling reuse/repairing and access to high value components (Parajuly et al. 2016). Material choices like single plastics would allow for purer material streams and improve recycling rates (Laurenti et al. 2015) .

However, success of these CE strategies in the electronics sector depends heavily on the behavior and decisions of end users as a key stakeholder group. For example, modest energy efficiency and material reduction gains from technological advancements dematerialization, material and product substitution, or reducing standby energy continue to be offset by increasing product functionality, increasing ownership, and use behaviors (Babbitt et al. 2018; Kasulaitis et al. 2015, 2018; Ryen et al. 2015). Because consumers lack awareness or control of factors causing impacts (e.g., material and energy intensity), holistic, human-centered design strategies are critical to nudging users towards behaviors that will facilitate a more circular economy (Lilley 2009; Komeijani et al. 2016). Sparking consumer interest in used products may require innovations to communicate distinctiveness or provide unique consumption experiences (Weelden et al. 2016; Wieser 2016; GEC 2018).

Similar to challenges identified for food waste, CE in the electronics sector is also heavily dependent on concurrent changes in *waste collection and management infrastructure* needed to promote reuse and enable greater material recovery, thus enhancing environmental and economic benefits (Williams et al. 2008; Kumar et al. 2017; Zeng et al. 2016; Benton and Hazell 2015). This requires clearly defined stakeholder responsibilities and meaningful collaborations among parties involved (Zhang et al. 2015; Parajuly and Wenzel 2017). Japan's CE success has been attributed to manufacturers financially invested in repair/recycling industries, consumer friendly and convenient collection systems, and upfront consumer fees (Salhofer et al. 2016; Borthakur and Govind 2017; Benton and Hazell 2015). Proper handling and storage for reuse items is needed to minimize damage (Coughlan et al. 2018) and tools are needed to test and prepare items for reuse (Bovea et al. 2016), enabling third parties to repair, remanufacture or recycle devices (Laurenti et al. 2015; Vanegas et al. 2018) and limit use of heuristics (e.g., model or color; Ryen et al. 2018; GEC 2009). Information and decision tools ease uncertainty from material stream volatility stemming from introduction of new plastics, lower quantities of high valued precious metals, larger quantities of low value plastics, and supply chain disruptions (Chancerel et al. 2013; Sprecher et al. 2014; Cucchiella et al. 2015). Data plays a key role in this challenge, particularly as new technologies like data analytics, sensing technologies, and artificial intelligence (Nobre and Tavares 2017) may contribute to greater stakeholder information and communication. These technologies can encourage more efficient, flexible material management systems that can adapt to the quickly changing product and material stream (Ryen et al. 2018) and provide much-needed data for assessing environmental benefits via LCA and MFA methodologies.

Literature has also emphasized the connection between CE strategies for electronics and existing e-waste management take back and extended producer policies. Some of the key challenges include mass-based policy standards that only focus on recycling and recovery of heavier, legacy devices (Gui et al. 2013), outsourcing responsibility to third party collection systems (Singh and Ordoñez 2016), confusing responsibility among stakeholders (Li et al. 2015). Consideration how consumers value used devices can influence policies; point of sale fees may be more effective in the U.S. as devices have little to no value, in comparison to consumers in China or India who can sell obsolete devices (Borthakur and Govind 2017). Recent National Sword policies restricting export of e-waste to China and other Asian countries (Peterson 2018; Ramodetta 2018) may be the tipping point to formalize recovery and reuse structures (Eng 2018). Inspiration from a true circular economy, our natural system, can stimulate innovative resource management Laurenti tools based on the concepts of foraging or searching for food (Ryen et al. 2018) or role of 'scavengers' to process resources (Ghisellini et al. 2016). Sharing is an untapped opportunity to reduce consumption with subscription, sharing, or product service systems (PSS) models like smartphone PSS (Bridgens et al. 2017), software enabling computer sharing among users, but require policy support, integration of design and business strategies (Moreno, et al. 2016), a mindset of collaboration (Vanegas et al. 2018). Successful transition towards a CE centers on consumers and approaches that integrate changes in technology, design strategies, infrastructure, policy, and business models.

Buildings and infrastructure

Construction of the built environment (including buildings and infrastructure) consumes significant resources and demolition in the sector generates a lot of waste. Global extraction of construction minerals exceeds 10 billion metric tons annually and has had the fastest growth rate of any sector over the past century (Fischer-Kowalski, et al. 2011). The United States generates over 550 million tons of construction and demolition (C&D) waste per year, which is more than twice the amount of generated municipal solid waste (US Environmental Protection Angency 2018). Thus, the built environment is a critical sector to consider in discussions of sustainable materials management. However, CE principles are challenging to apply in the built environment because of buildings' and infrastructure's long life, size, location (i.e., adjacent to other buildings or infrastructure), and complexity (i.e., commingling of materials and assemblies).

There have been numerous proposals for CE frameworks and strategies in the built environment as a means of improving resource efficiency in the sector (Foster 2020; Pomponi and Moncaster 2017). The strategies are generally proposed within the ReSOLVE framework proposed by the Ellen MacArthur Foundation that includes six ways to apply circularity: regenerate, share, optimize, loop, virtualize, and exchange (Foresight 2016; Carra and Magdani 2017; Ellen Mac Arthur Foundation 2016). Specific strategies for the built environment include reducing C&D waste, maximizing value from C&D waste, designing for material and component reuse, designing for long life and adaptability, enabling CE design and construction practices through increased use of digital technology and advanced automation, and transforming finance mechanisms and regulations to incentivize CE strategies. Case studies for buildings have been presented to demonstrate the feasibility of implementing some of the strategies (Leising et al. 2018; Ellen Mac Arthur Foundation 2016). There is a dearth of case studies for infrastructure, although case studies involving paving materials are emerging in the context of CE (Mantalovas and Di Mino 2019; Mantalovas et al. 2020; Calabi-Floody et al. 2020). Research on CE strategies for the built environment is typically focused on a single strategy, such as the use of recycled content in new materials, reuse of components, or modularization (Mantalovas and Di Mino 2019; Minunno et al. 2018; Calabi-Floody et al. 2020; Mignacca et al. 2020). Such analyses are an important for guiding implementation of CE strategies because they provide insight on technical and design issues. However, it is now essential that the scope of CE research on the built environment expand to quantitatively evaluate trade-offs among various strategies and other performance objectives in a holistic fashion. For example, there may be trade-offs between the use recycled content and the durability of infrastructure, or between design for adaptability and the energy efficiency or resiliency of a building. There also may be trade-offs among environmental impacts (e.g., a reduced greenhouse gas footprint but an increased water footprint).

Evaluating the environmental impacts of CE strategies requires the comparison of innovative design solutions for buildings and infrastructure using life cycle assessment and industrial ecology methods (Hossain and Ng 2018). Given the hypothetical nature of evaluating strategies not currently used and the systems implications of changing secondary material streams, consequential LCA will be an important tool for quantifying impacts. In addition, MFA and systems dynamics will be required to understand the implications of shifts in materials markets due to increases or decreases in secondary material flows. However, it is important not to overlook the vital role that new and innovative building and infrastructure design, materials, and construction solutions will have in improving resource efficiency. New business models will also be required to implement CE strategies in the marketplace (Munaro et al. 2020). Using the ReSOLVE framework for buildings and infrastructure in new and effective ways will be challenging, but quantitative assessments of the life cycle environmental impacts of CE strategies will be a key component of their implementation.

Cross-cutting themes

The keyword mapping analysis (Fig. 1) and the sectoral-specific analysis illuminated several cross-cutting themes that are critical to addressing the sectoral CE challenges and implementing CE strategies. These four themes and their challenges and opportunities related to increasing CE adoption are shown in Fig. 4. There is more extensive literature on the use of models and business/innovation in support of CE analyses and hence, they are treated more in-depth.

Decision-oriented data

The challenge of obtaining high quality, transparent data spans all sectors and methods reviewed. In some cases, CE analyses require highly resolved data, such as compositional profile of materials feeding into CE pathways, variability of resource flows over time, or presence of contaminants that may limit recycling or reuse, particularly in the case of chemicals and metals. In several sectors, data on alternatives are scarce, limiting the ability to identify functionally-equivalent chemical and metal substitutes or make "matches" with secondary markets to either obtain recovered resources or find an end-of-life pathway. Particularly in the case of buildings and electronics, data to characterize realistic user behavior are required to analyze the full outcomes of CE strategies, where consumers may ultimately use products in ways that limit environmental benefits. Regionally-resolved data are also critical for advancing dynamic and spatially-explicit models, which are not yet widely used in CE studies.

On the other hand, the current boom in data science initiatives and improved computing infrastructures may provide new opportunities to overcome these data challenges. An open source or collaborative approach not only improves the availability of data but also democratizes the process of data scrutiny and validation. Harmonization of data within and across sectors using such platforms may also lead to greater comparability and consistency across studies. However, incentives may be required to encourage researchers to participate. The Virtual Industrial Ecology laboratory (https://ielab.info/) provides a successful example of a collaborative platform used to overcome data challenges in implementing a theoretical framework.

Modeling to assess circular economy outcomes

Implementing CE solutions across the diverse sectors described above introduces new challenges of modeling multiple systems interacting at different spatial and temporal scales and evaluating implementation to ensure it leads to net environmental benefits. Systems modeling methods such as LCA and material flow analysis MFA are natural choices to analyze the costs and benefits of reconfiguring sectors to achieve CE goals. LCA and MFA are widely used in the field of industrial ecology, which shares the aspirations of closing resource loops and converting wastes to resources. These methods have a clear role in informing holistic decisions for CE transitions but also face key modeling challenges that have yet to be fully addressed. This section reviews the current applications

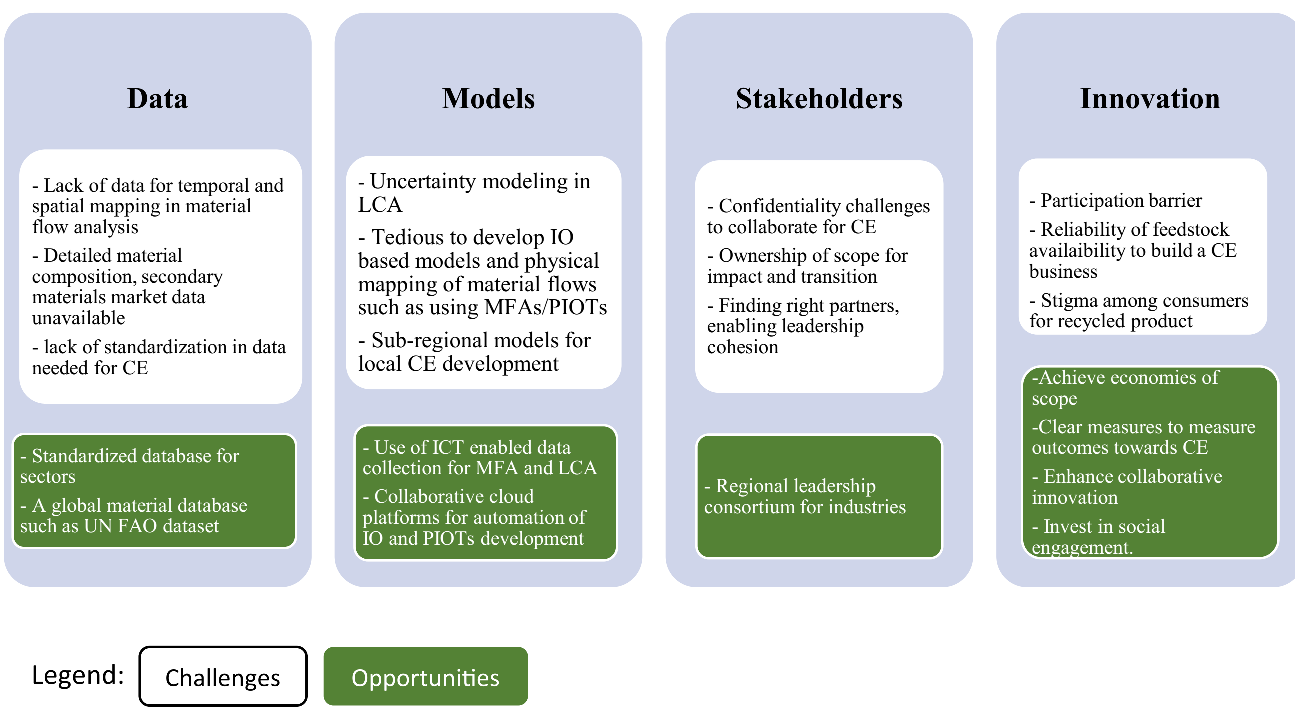

Fig. 4 Key Challenges and Opportunities for cross-cutting themes that are critical to implementing CE strategies in the sectors

of LCA, MFA and IO based models in CE and also raises opportunities for methodological innovation.

Life Cycle Assessment

LCA is a holistic system modeling approach for assessing environmental impacts of a product system throughout its entire life. This method can be applied to evaluate circularity interventions designed to minimize or recover waste in product systems (Edwards and Crossin 2017; Maga et al. 2019, Morris 2005), such as anaerobic co-digestion of organic waste (Edwards and Crossin 2017), mechanical and chemical recycling for waste polylactic acid (PLA; Maga et al. 2019), curbside recycling programs (Morris 2005), and e-waste management systems (De Meester et al. 2019). LCA research has also been applied to product systems that incorporate CE principles to production operations or supply chains. For example, LCA has been applied to confirm the environmental benefits of industrial symbiosis (Daddi et al. 2017, Deschamps et al. 2018, Eckelman and Chertow 2013, Mathur et al. 2020) and guide process development of byproduct and waste valorization systems (Robertz et al. 2015; Seto et al. 2017; Khoshnevisan et al.,2020; Lam and Hsu 2018). LCA has been applied to a wide array of waste repurposing cases, such as agricultural products (Hong et al. 2015), aquaculture systems (Strazza et al. 2015), aerospace alloys (Eckelman 2014), grey water systems (Yoonus and Al-Ghamdi 2020), algae biodiesel (Gnansounou and Raman 2016), aluminum cans (Niero and Olsen 2016), municipal food and solid waste management (Edwards and Crossin 2017; Saraiva et al. 2017), product service systems (Brezet et al. 2016), the construction industry (Rios et al. 2019), and regional development (Eckelman and Chertow 2009a, b). CE-oriented waste-to-energy systems, discussed more in the context of food waste in Sect. 4.1, have also been analyzed extensively using LCA (Lazarevic et al. 2010, Aziz et al. 2019, Esteves et al. 2019, Ingrao et al. 2019, Rajendran and Murthy 2019) primarily to evaluate effectiveness of these systems for relieving energy-related environmental burdens (IEA 2020).

The application of LCA to loop-closing approaches demonstrates the versatility of the method for evaluating CE strategies at all stages of implementation (Moraga et al. 2019a, b). A review on CE implementation tools highlights the role of LCA in sourcing materials to reduce supply chain impacts (Yuliya Kalmykova et al. 2018) and guiding design for closing loops through reuse, recycling or remanufacturing. LCA helps to highlight interactions between complex systems, such as the food-energy-water nexus (Del Borghi et al. 2020), and determine if a CE intervention creates net environmental benefits (Mohammed et al. 2018; Moraga et al. 2019a, b; (Chen et al. 2019). Metrics like the Material Circularity Indicator (MCI; Ellen MacArthur Foundation 2019) can be combined with LCA to provide parallel analysis of a product's circularity and environmental performance. Additionally, expanding LCA to incorporate 6R elements (reduce, reuse, recycle, recover, redesign, remanufacture), can facilitate evaluation of product lifespan extension strategies (I S Jawahir and Bradley 2016). LCA-based CE indicators can contribute to standardization efforts in evaluating CE performance (Pauliuk 2018), particularly when coupled with multi-criteria decision analysis to assess solutions under conflicting scenarios (Niero and Kalbar 2019a, b).

While research has demonstrated that LCA is of value in building a CE framework (Bakker et al. 2010), challenges exist in its implementation. Data availability and quality continue to be major challenges, potentially limiting accuracy of results (Cucurachi et al. 2018) and result in difficulty using LCA to evaluate if CE strategies create net environmental benefits. Another persistent concern is the choice of LCA system model. Even before LCA was widely applied in the CE context, experts and practitioners debated the circumstances that call for using either attributional LCA (ALCA) or consequential LCA (CLCA; Brander et al. 2019; Weidema et al. 2018). ALCA assigns the cumulative environmental impacts to all flows attributable to a product system at a fixed point in time, whereas CLCA measures the marginal impacts due to fulfilling the functional unit over time (Curran et al. 2005). In the CE context, CLCA may be essential to give a complete perspective on economy-level transitions or innovative services designed to disrupt and rearrange existing supply chain networks (Haupt and Zschokke 2016). On the other hand, ALCA may be better for describing environmental tradeoffs of a specific product or design alternative or to provide straightforward information to decision makers and aid in ecolabeling to promote CE adoption in the market. Considering the broader literature, some studies bridge the gap by carrying both an ALCA and CLCA (Jones et al. 2017; Venkatachalam et al. 2018; Yang 2016; Zanten et al. 2018), but this approach would magnify existing data challenges. To our knowledge, no literature has yet demonstrated the application of CLCA for modeling or decision making on CE implementation.

Material flow analysis and dynamics

MFA is "the systematic assessment of the flow and stock of materials within a system defined in space and time; it connects the sources, the pathways, and the intermediate and final sinks of a material" (Wen and Li 2010). As early as 1999, MFA was being used to describe and analyze sustainable development challenges, and by extension promoting CE (Ii et al. 1999). MFA can facilitate CE strategies by describing the location and composition of waste streams in the economy (Kuczenski and Geyer 2010), virgin resources yet to be extracted (Kesler et al. 2012), the accumulation of “urban mining” stocks (Eygen et al. 2016), the routes of resource loss (NRDC 2012), sites of high consumption (UNEP International Resource Panel) and the secondary resources not suitable for reuse because of their compositional quality or in-use dissipation (Ciacci et al. 2015). More recently, MFA has found extensive application in analyzing waste minimization and material flows in the context of recycling (Haupt and Zschokke 2016; Pivnenko et al. 2016). MFA has been applied to evaluate CE strategies for many of the sectors described in earlier sections, including biomass systems (Marques et al. 2020) e-waste (Cordova-Pizarro et al. 2019; De Meester et al. 2019) metals such as copper (Gorman and Dzombak 2020) and rare earth elements (REE; Guyonnet et al. 2015), and highway infrastructure (Wen and Li 2010). Recent literature has also connected MFA to business and innovation studies, for example, examining plastic flows as a precursor to CE innovation in a small island developing state (Millette et al. 2019a, b).

Despite methodological advances, the data-intense nature of MFA is a major barrier to more widespread application, as data quality and availability remain a challenge (Laner et al. 2015; Wang and Ma 2018). For example, CE implementation requires data that are highly resolved at the regional or material level (Virtanen 2019), but insufficient information about specific materials or processes makes it difficult to generate regional MFAs (Haas et al. 2015; Haas et al. 2016) to aid project development. In broader applications, MFA has been integrated with other tools; for instance, combining MFA and thermodynamic analysis to determine benefits of industrial symbiosis and thereby provide evidence to stakeholders on the value of CE (Sun et al. 2017a, b). MFA in combination with LCA may be useful to analyze both economic and environmental factors of a CE pathway (Pomponi and Moncaster 2017a, b). Modeling the transition towards CE also calls for methods that account for change over time, such as MFA combined with system dynamics (Gao et al. 2020) or models that reflect changing socio-economic metabolism (Paulik and Hertwich 2016). Recent work proposed economy-wide material flow accounting (ew-MFA) to estimate the generation of in-use stocks and waste generation over multiple years (Wiedenhofer et al. 2019) and ew-MFA has been integrated with global dynamic models to simulate circular economy scenarios at the global level (Hanumante et al. 2019). Data gaps can also be bridged using technology forecasting methods to enable scenario analysis (Althaf et al. 2019) or uncertainty analysis when detailed material composition data are not available (Arowosola and Gaustad 2019). Key opportunities for future research include developing and validating MFA models for data-scarce scenarios and coupling MFA with systems-level environmental or economic tools, as is discussed in the following section.

Input–output based models

The macroeconomic framework of input–output (IO) models provides a robust methodology for understanding complex interactions and structural interdependence between sectors of an economic system (Leontief 1991) and between these sectors and the environment (Leontief 1970a, b, c). Since redesigning physical systems towards CE will require systems transformations, IO models provide a suitable theoretical framework, despite their relatively low use in CE studies to date. Of particular promise are modifications such as environmentally extended input–output (EEIO; Leontief 1970a, b, c; Matthews and Small 2001) and integration with MFA (Nakamura et al. 2007; Pfaff et al. 2018; Duchin and Levine 2019). For example, EEIO-based studies have assessed economic and environmental impacts CE strategies like waste reuse, product lifetime extension, closing material loops, and improving resource efficiency (Aguilar-Hernandez 2019; Donati et al. 2020). Methodologically, using EEIO methods to evaluate CE strategies will also require more data that capture structural changes due to increasing recycled materials markets or marginally reducing demand due to product life cycle extension.

Various approaches have been taken to use IO analysis in conjunction with MFA for evaluating CE scenarios (Surahman et al. 2017; Schiller et al. 2017), with the waste input–output MFA model (WIO-MFA) being one of the most established and widely used frameworks for IO-based CE studies (Towa et al. 2020). The model converts a monetary IO table into a physical input–output table (PIOT), enabling analysis of product composition and material intensity (Nakamura et al. 2007; Lenzen and Reynolds 2014). Through its dynamic-MFA extension (Nakamura and Kondo 2018), based on the MFA model MaTrace (Nakamura et al. 2014, 2017), WIO-MFA also enables consideration of changes in secondary material composition over time due to reuse and maintains supply–demand balance for the material under investigation. In addition, the utility of EEIO and integrated IO-MFA for CE analysis may be further supplemented by integrating location-specific conditions through multiregional input–output (MRIO) models (Tisserant et al. 2017; Stadler et al. 2018) and open source tools (Donati et al. 2020).

However, one major limitation of applying EEIO approaches to CE is that while these models are clearly able to simulate the impacts of all the strategies to achieve CE, their monetary-based analyses do not fully represent actual physical transitions in the economy (Hubacek and Giljum 2003; Weisz and Duchin 2006). One way to improve CE insights gained from EEIO models is creation of hybrid and physical input–output table (PIOT) models (Hawkins et al. 2007; Hoekstra 2010; Kovanda 2018). Recent work focuses on hybrid Supply-Use Tables (HSUTs), which can form a precursor for IO tables (Merciai and Schmidt 2018a, b), although implementation to make such tables available to the research community is still required. PIOTs will be particularly valuable for optimizing resource flows in the economy, given their ability to track a specific material flow through the whole system. In this sense, PIOTs share similarity with MFAs, but can connect underlying mass flows to economic production, leading to calculation of material intensity per unit of production from any sector (Singh et al. 2017). While this method can model structural changes as a result of transition to CE, PIOTs are data intensive and not yet widely used to inform strategic decisions (Hoekstra 2010). One solution to this issue may be in the combination of process engineering models with the IO framework (Wachs and Singh 2018). In this approach, process models of production provide physical data to build PIOTs using a bottom up approach which could then be extended to develop a computational algorithm for standardizing the "Process to PIOT" approach (Vunnava and Singh 2019). The strengths of this bottom up approach are modularity, reproducibility, and potential for automation (Vunnava et al. 2020; Singh et al. 2017). Developing these PIOTs may also benefit CE studies by providing regional data needed to implement MFA and contributing to WIO methods (Lenzen and Reynolds 2014) that evaluate the impact of waste recycling.

Stakeholder engagement

Advances in data and modeling cannot be viewed as an end goal, even if that is where much of the literature stops in CE case studies, but rather as a conduit to providing actionable information to stakeholders. While stakeholders are an explicit consideration in literature focused on circular business models, they are typically treated implicitly in sectoral studies (Rothenberg et al. 2020; Halloran et al. 2014)(Hagelüken et al. 2016; Zhang et al. 2015). However, industry, academic, governance, consumers, and supply chain stakeholders, among others, will all play a key role in generating data, recognizing the value proposition of CE strategies, and ultimately changing business and innovation practices across the value chain (Moreno, et al. 2016; Vanegas et al. 2018; Perey et al. 2018; 2017a, b; Lenzen and Reynolds 2014; Ehrlichman et al. 2018). Literature points to a wide array of technical barriers facing stakeholders, including challenges identifying functional substitutes for high-impact resources, creating low-cost cleaner production systems, implementing technical solutions for product lifespan extension, and deploying more efficient, scalable remanufacturing, recycling, and material recovery systems (Mantalovas and Di Mino 2019; Mantalovas et al. 2020; Calabi-Floody et al. 2020; Kumar et al. 2017; (Geisendorf and Pietrulla 2018; Bocken et al. 2014; Wever 2012). In parallel, market barriers also hinder stakeholder action on CE that is outside a primary business function or revenue stream (Nghiem et al. 2017; De Clercq et al. 2016). Parallel research and innovation in Internet of Things, blockchain solutions, and data-driven analyses along with data-driven manufacturing can enhance models that convey the 'business case' for CE strategies (Nobre and Tavares 2017; Carra and Magdani 2017; Ellen Mac Arthur Foundation 2016; Kovacova et al. 2020). Further, research into education, engagement, and incentives will play a key role in understanding how consumers can become part of CE solutions (Wieser 2016; Midgley et al. 2017).

Business and innovation

Literature on CE implementation clearly revolves around issues surrounding current business models and opportunities for innovation (Rothenberg et al. 2020; Fig. 1). Current material use patterns in economic sectors described in Sect. 3 are predicated on ideas developed during for the Industrial Revolution that exploited specialization of labor and economies of scale to increase efficiency (Hounshell 1985). As increased efficiencies allowed for lower prices, unit sales increased, thereby enabling even greater economies of scale and specialization of labor (Taylor 1911). For decades, the positive feedback loop of industrialization drove pseudo-exponential growth in material demands (Berkhout and Hertin 2004). However, in the late 1960s, the economy began to press against the biophysical limits of technologies for primary materials extraction, and planetary support systems for waste disposal (Ayres 2006). This trend was anticipated by a now-famous article that contrasted the "cowboy" economy predicated on ever-expanding domestication of an open frontier, and a "spaceship" economy predicated on reuse and recycling of material streams within "a closed sphere of human activity" (Boulding 1966) .

The transition to a circular economy is an extension of the spaceship metaphor, in which returns will not accrue to scale, but from an increased capacity to utilize materials that were previously discarded (Ellen Macarthur Foundation 2019). More recently, the exploitation of new information-communication technologies (ICT) in old industries such as hotel, taxi, and manufacturing may be a new avenue for wringing efficiencies from the economy (Denning 2014; Cusumano 2015; Denning 2014; Cusumano 2015; Posen 2015). In a technologically optimistic version of the transition to CE, adding information technologies (e.g., waste sorting), allows improvements in quality of life without pressing against thermodynamic limits that presage biophysical collapse. Where ICT can substitute for material redundancies and reduce waste, knowledge becomes the "ultimate resource," and could hypothetically be unlimited (Simon 1981).

In the old model of industrialization, innovation could occur at a single point in the supply chain, without necessitating management of feedback loops in material flows that increase complexity and scarcity. Further, standardization ensured both economies of scale and substitutability of parts (and labor), allowing innovators to plug into existing production systems provided they met expectations of compatibility with existing standards. Whereas, a post-industrial model of innovation for a circular economy must operate at the larger scale of the entire system (Midgley et al. 2017), because recovery of post-consumer goods for reuse, remanufacturing, or recycling creates feedback loops that present complicated materials management issues, including collection, sorting, treatment, and reintegration into the economy.

Complex challenges, such as circular economy, require a shift in the paradigm of innovation as described by the early works of (Kuhn 1996). Transitions to CE will require overcoming barriers to innovation that would be insurmountable without system-wide innovation as shown in Figure. Despite massive generation of waste materials in American urban centers, the problem of *securing a reliable source of post-consumer feedstock* presents extraordinary risks to circular economy entrepreneurs (OECD 2019). Without consistent sources of "waste" material, technology and business models must be designed for flexibility, adaptability, and agility, at the expense of efficiency. These demands drive-up short-term costs and business risks. The *economies of scale* typical of centralized production systems have to be replaced by *economies of scope*, in which the cost of any item becomes cheaper *not* as the scale of the market for identical items expands, but as the *diversity* of the market of *differentiated items* increases (Geisendorf and Pietrulla 2018). To achieve this economy, advances in technologies for the beneficial reuse of waste- and by-products must continue to become more sophisticated (Fig. 5).

Products derived from waste or used materials still suffer from a stigma that makes customers reluctant to become early adopters (Wieser 2016). The transition to a circular economy based on economies of scope will require thousands, if not millions, of customers willing to become early adopters. Innovative business models will take time to become adopted among consumers and organizations (Rogers 2003) and will require changing how we view who participates in innovation, what the process of innovation looks like, and what the outcomes of innovation are (Midgley et al. 2017) .

The logistics of material flows, and consumption or use patterns for products and services currently neglect the "true" holistic value of discarded materials versus virgin materials (Hedberg et al. 2019). To resolve these issues, seamless collection, sharing, and *integration of data* across value chains is necessary to drive data-informed decisions. Addressing systemic problems requires coordinated system-wide solutions, and this necessitates a concerted effort from a broad range of *stakeholders* that work to create enabling conditions for effective collaborations (Ehrlichman et al.

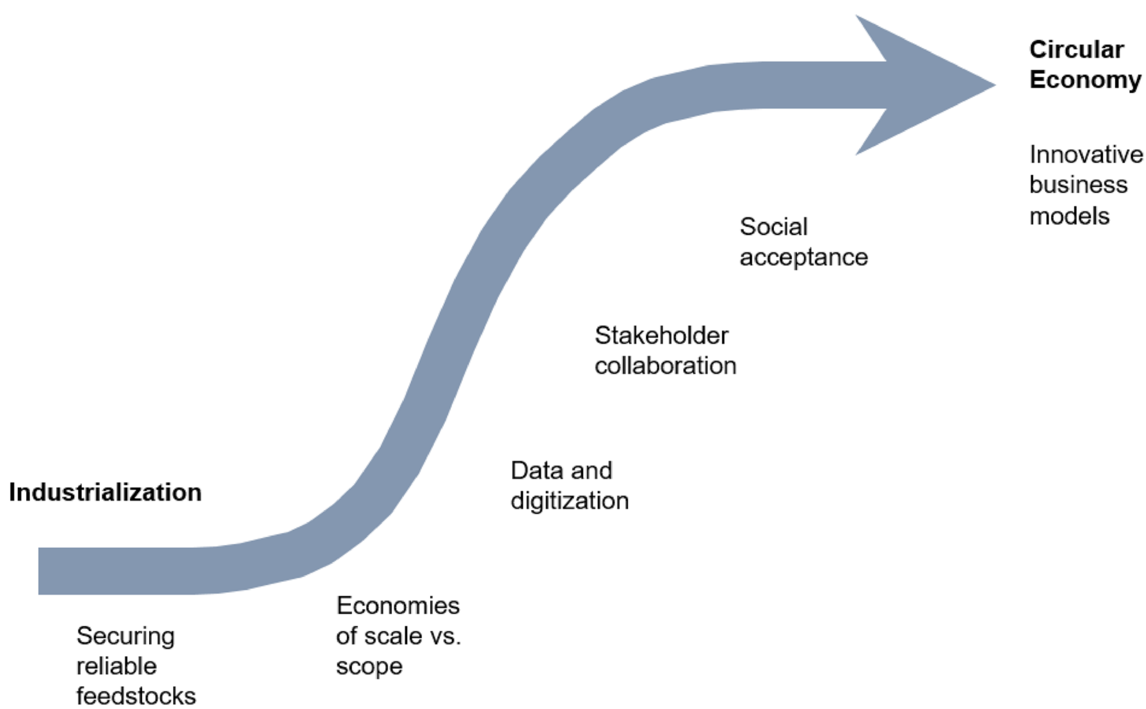

Fig. 5 Overcoming barriers to enable a paradigmatic shift to a circular economy

2018) among institutions, industries, and regions. For centuries, the feudal model of the *master architect* has dominated our concept of how innovation takes place. Although it has long been acknowledged that collaboration and knowledge sharing are essential to creativity and innovation (e.g., Johnson 2010), the myth of the lone genius has nevertheless persisted in the public imagination (e.g., Ashton 2015).

An intention-based approach to innovation may be curated, structured, and conform to standards, even while allowing the result to emerge. Systemic innovation leverages open source experiments and porous organizational boundaries (Mazzucato 2018). In systemic innovation, contributions may not be attributable to any single innovator or inventor, given that at the scale of the whole system, individual contributions sometimes cannot be disaggregated from the whole. Paradigm shifts such as these have the ability to drive radical innovation, which could result in unpredictable and disruptive changes to the industrial paradigm of centralized and hierarchical control (Kuhn 1962). From this, new systems could be developed by changing stakeholder's thinking, relationships, interactions and actions.

The concept of a circular economy is a fundamental departure from modern economic theory, but much of the literature is focused on incremental, rather than radical, innovation. In many of the sectors reviewed, continued progress along the current trajectory will lead to significant gains. Several examples are shown in Figs. 2 and 4 of innovative opportunities with significant potential for future research, such as complete depolymerization to recover valuable raw materials and manage the growing plastic waste challenge or the use of electronics to fundamentally shift consumers' daily behaviors towards sustainable choices. Among enablers creating automated cloud-based platform that enables stakeholder engagement with insights from theoretical model will provide significant advancement in implementation strategies. A review of CE business models also points to critical opportunities and barriers to radical innovation and the attendant paradigm shift required for this transition. Two such priorities for future CE innovation research are the ability to achieve economies of scope, rather than economies of scale, and the potential for ICT and digitization to replace resource-intense products and services. Access to data, stakeholder collaboration and communication, and clear methodologies to measure outcomes are also critical elements that enable each industrial sector to address circular economy challenges and force a shift in the creation and adoption of innovative business models.

Conclusion

A wide body of research exists on CE implementation and this breadth points to clear progress at a theoretical level to both create innovative solutions and develop methods needed to assess the outcomes of their application. Existing CE reviews focus on definitions of CE, regional developments or focusing on opportunities in few single sectors. However, evidence of real implementation in sectors is less prevalent, and the literature remains relatively fragmented, where lessons learned from one sector are not necessarily conveyed to others and new business models are not fully validated in realistic case studies. Further methodologies are not consistently applied or there is a lack of standardization in use of modeling techniques to inform transition to CE. The findings from this literature review have implications on both fundamental research and investments in scale-up of clean technologies that can facilitate the transition to CE. The complex challenges and structure of the CE transition magnify the cross-cutting challenges in collecting data and implementing methods that have been largely adopted from the industrial ecology field. However, the diverse nature of CE stakeholders also offers promises for solutions to these challenges, through new approaches to coordination, data sharing, and estimating the value proposition of CE solutions. Further, CE pathways provide a novel testing ground to understand social adaptation for recycling, radical innovation towards economies of scope, and technical advances that will transform material management and recovery loops.

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