The application of blockchain technology in the recycling chain: a state-of-the-art literature review and conceptual framework

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Abstract

More practitioners are embracing blockchain technology to improve recycling performance. However, current research on the use of blockchain is mostly confined to general discussions on sustainable supply chains and circular economy, with limited studies specifically focusing on the recycling chain. This paper conducts a thorough content-based review of the literature related to the application of blockchain technology in the recycling chain with the objective to identify a conceptual framework. Although descriptive and thematic analyses show limited developments, blockchain technology can offer four distinct functions in the recycling chain: transparency, integration, behaviour channelisation, and service transformation. The adoption of blockchain in this area has technical, organisational, and environmental limitations that have not been overcome yet. In terms of benefits, blockchain technology improves recycling performance in terms of cost, dependability, flexibility, sustainability, and risk reduction. To summarise the findings, the paper proposes a novel conceptual framework for blockchain implementations in the recycling chain to support practitioners and guide scholars in further blockchain technology exploration.

Keywords: blockchain technology; recycling chain; sustainable supply chain; literature review; sustainability

1. Introduction

According to a global waste management report by The World Bank, waste generation is surging at an alarming rate and is expected to grow twice as fast as population growth, reaching 3.88 billion tonnes by 2050 Kaza et al. (2018). At the heart of sustainability, in addition to prioritising the reduction of waste generation, recycling primarily involves the collection and transformation of waste into usable and new materials, which can reduce the extraction and consumption of raw materials and empower the value to waste (OECD 2022). Particularly for high-value recyclables such as metals and electronics, recycling will be a catalyst to increase the sustainability value of these products (Wang and Wang 2019; Jalali et al. 2022). However, the traditional linear model following 'take-make-dispose' still prevails. In the case of plastic waste, the OECD reports that only 9% of plastic is recycled globally, as mismanaged disposal methods such as landfill and incineration still dominate (OECD 2022).

From a macro level, the global recycling trade is traditionally dumped into developing countries for further processing. In the past, China received more than half of global waste. However, China enacted the ban on importing waste in 2017 and, since then, the global waste trade has been significantly reshaped (Wen et al. 2021). The ripple effects of China's ban significantly affected global waste management and illegal dumping and disordered waste disposal processes commonly exist (Howson 2020). For example, there are huge discrepancies between the officially recorded volume of plastic waste and the real exports, and much is still illegally transported to the Far East (Wen et al. 2021).

Also, more salient chaotic issues exist at the micro level. Some individuals hold the attitude of 'out of sight out of mind' when it comes to waste sorting (Chidepatil et al. 2020); Manufacturers neglect sustainable packaging material designs and focus solely on the pursuit of profits (Batista et al. 2019; Ajwani-Ramchandani et al. 2021); most back-end waste processing is handled by third parties without transparent auditing; regulations for different waste categories are insufficient (Li et al. 2017; Gu et al. 2019). In addition, the lack of trust among stakeholders poses threats to traceability in recycling chains. For example, remanufacturers need to have an in-depth knowledge of product components to conduct recycling or remanufacturing processes. However, most product lifecycle information is interrupted after selling to customers and these disclosures are essential to enhance consumer confidence as well as regulatory supervision (Tozanlı, Kongar, and Gupta 2020; Zhu, Kouhizadeh, and Sarkis 2022). Therefore, it is urgent to identify proper solutions to tackle the global recycling crisis.

As one emerging information technology under the 'Industry 4.0' umbrella (Nayernia, Bahemia, and Papagiannidis 2022), blockchain technology (BCT) is expected to tackle the above issues. BCT originated from Bitcoin and extended rapidly to other fields, particularly into supply chain management (SCM) (Saberi et al. 2019; Wang, Han, and Beynon-Davies 2019; Koh, Dolgui, and Sarkis 2020; Pournader et al. 2020). The inherent transparency, immutability and decentralised features of BCT demonstrate aspirational applications for sustainability, traceability and authentication, such as the increasing applications in the food (Li, Lee, and Gharehgozli 2021), logistics (Pournader et al. 2020), cross-border trade (Chang, Iakovou, and Shi 2020), pharmaceutical (Ghadge et al. 2022) and maritime sectors (Liu, Zhang, and Zhen 2021). Moreover, BCT demonstrates rich functionality in platform operations, including information disclosure, platform pricing, consumer decision making and SCM coordination (Tozanlı, Kongar, and Gupta 2020; Xu et al. 2021; Shi, Yao, and Luo 2021).

In recycling, França et al. (2020) proposed that 'social coins' empowered by BCT can incentivise communities' recycling activities in a Brazilian municipality. By adopting multiple case studies, Gong, Wang, et al. (2022) explored a BCT-based solution for marine plastic debris management. Esmaeilian et al. (2020) proposed the potential of BCT to enhance product lifecycle visualisation and improve sustainable reporting and monitoring. Some research has identified the challenges of BCT-based waste management: Taylor, Steenmans, and Steenmans (2020) pointed out the waste property rights and privacy issues, and Gong, Xie, et al. (2022) identified four barriers – cognitive, technical, internal, and external – to embedding BCT in the recycling industry.

BCT-based recycling initiatives have been carried out in a few pioneering companies worldwide such as Plastics Bank, Empower and RecycleGO with continuously expanding applications, which suggest that current research is behind practice (Chaudhuri, Subramanian, and Dora 2022; Gong, Xie, et al. 2022). Previous studies discussed potential BCT applications for recycling using scattered views and fragmented research articles (e.g., generally mentioned in BCT and sustainability, circular economy studies) (Saberi et al. 2019; Bai and Sarkis 2020; Manupati et al. 2020; Tozanlı, Kongar, and Gupta 2020). Most of the literature proposes that BCT could be a potential solution, but it does not comprehensively consider under what circumstances BCT can solve specific recycling issues (e.g., trust and information asymmetry issues). The distinct innovations and successful implementations of BCT received growing attention in SCM, particularly in the form of a growing number of literature review articles (Pournader et al. 2020; Karakas, Acar, and Kucukaltan 2021; Liu, Zhang, and Zhen 2021; Ghadge et al. 2022). However, a thorough or systematic literature review discussing BCT interfacing with the recycling chain is still missing. Thus, this paper aims to provide an overview of BCT and recycling chains by answering the following research question: *How can blockchain technology be applied in recycling chains?*

This research reviews the current research status of BCT applications in recycling chains and proposes a novel conceptual framework. It systematically maps the functions, potential performance, and feasibility limitations of BCT in recycling chains, and the proposed conceptual framework elucidates the logical process of BCT adoption. Also, it enriches limited research in recycling from the SCM perspective and responds to Erhun, Kraft, and Wijnsma (2021)'s calls for research on technology adoption in SCM for sustainability. More importantly, this study offers innovative and feasible solutions for tackling the waste crisis in practice and paves the way for relevant implications for scholars and practitioners interested in achieving sustainability through BCT application.

This paper is organised as follows. Section 2 provides background information on the recycling dilemma and BCT essentials derived from relevant studies. Section 3 systematically presents the review method. Section 4 conducts the descriptive analysis and Section 5 illustrates detailed thematic analysis findings. Section 6 proposes a conceptual framework. Finally, conclusions, future research directions, and limitations are summarised in Section 7.

2. Literature Review

2.1 Recycling chain dilemma

'Reduce' is the main priority to achieve 'zero waste' (Abbey and Guide 2018; Turken et al. 2020). In addition to reducing waste generation, recycling performance can be enhanced via a SCM perspective (Field and Sroufe 2007; de Lima, Seuring, and Sauer 2021; Gong, Xie, et al. 2022). However, thorny issues still exist, including the lack of recycling awareness and enforcement, destructive waste disposal, social inclusion difficulties, waste flow tracking chaos, and uncoordinated recycling chains.

Lack of recycling awareness and enforcement: Traditionally, the attitude of companies towards waste management is highly dependent on economic values. If the cost of recycling is too high – i.e., the cost of processing recycled materials is higher than the use of raw materials – then the incentive to recycle would be limited (Pagell, Wu, and Murthy 2007). Most original equipment manufacturers are economically driven to recover recycled materials, but they often face the dilemma of whether to form coopetition or competition with social collectors to capture the optimal recycling benefits (Jalali et al. 2022).

Although recycling awareness is increasing, initiatives on how to effectively encourage participation (e.g., waste sorting) are lacking (Liu, Zhang, and Medda 2021). Coercive policies may be effective in the short term, but awareness needs to be developed over time as relapses in waste sorting behaviour are common. Moreover, people may only care about the products' ownership or quality but ignore post-consumption responsibility. The responsibility for waste products generates the design of the extended producer responsibility (EPR) system, which stipulates that the producer's responsibility for products extends to the post-consumer stage (Gu et al. 2019). However, the division of responsibility in the EPR is often opaque and lacks effective incentives (Li et al. 2017). In practice, producers often attach post-consumer disposal costs to product price – i.e., shifting the responsibility to consumers. These conflicts again regarding the enforcement and clarity of responsibility stem from the lack of recycling awareness (Gu et al. 2019).

Destructive waste disposal: Some disposal approaches such as incineration and landfill can be devastating- more than 40% of global waste was disposed of in landfills while the percentage of proper recycled waste was only 20% (Kaza et al. 2018). Landfill and incineration methods often cause additional environmental pollution and may not apply to all waste categories (e.g., textile waste), resulting in wasted land and harmful emissions (Wen et al. 2021). In industrial production, manufacturers usually claim that they pass waste through qualified treatment. However, the monitoring of waste disposal is complex and multi-layered, making it difficult to develop an effective full chain of custody (Li et al. 2017). Following the 'reduce-reuse-recycle-disposal' principle, it is necessary to reduce destructive waste disposal first and then seek innovative solutions for reusing and recycling.

Social inclusion difficulties: Recycling issues are also contributing to urban development crises, particularly in developing countries, with more than 15 million people dependent on waste collection for their livelihood (Kaza et al. 2018). Known as "Waster Pickers (WPs)", they are street pickers or vendors who conduct waste collection, cleaning and reselling of collected waste to recyclers or manufacturers. They contribute significantly to waste collection but are seriously lacking waste disposal equipment and normally work in poor and hazardous environments (Gong, Xie, et al. 2022).

Most WPs are the elder group with lower education levels. They lack the ability to compete and be employed, and they are in a chronically poor situation, often with no recognised status (Ajwani-Ramchandani et al. 2021). With the acceleration of urbanisation, the number of these traditional WPs will gradually decrease and be replaced by formal recycling departments. It is necessary to integrate informal sector people into the recycling chain and focus on their contribution and social welfare (Gong et al. 2021).

Waste flow tracking chaos: To embrace waste flow supervision, comprehensive lifecycle tracking is imperative. In the forward supply chain, which is also the traditional manufacturing process, materials move from upstream raw material suppliers to downstream processing plants. The involved multi-tier supply chain networks often create monitoring difficulties with sustainability (Wilhelm et al. 2016; Gong et al. 2018). In the reverse supply chain, which takes used products from various channels to make new products, the lack of reliable waste information can trigger trust issues (Pagell, Wu, and Murthy 2007). For instance, recyclers can take advantage of information asymmetry to resell waste while manufacturers claim that they use recycled products (with higher prices) (Ambilkar et al. 2022; Jalali et al. 2022). People cannot verify the authenticity of renewable materials efficiently, and consumers usually rely on certifications claimed by brands or third parties (Gu et al. 2019). However, such greenwash scandals undermine consumers' confidence.

Moreover, waste tracking exacerbates accountability issues, particularly when wastes are sorted and crushed into smaller components (Taylor, Steenmans, and Steenmans 2020). After transporting waste products to recycling centres, the relevant information is missing as manufacturers usually have no control over the whole recycling chain, and then product information is opaque to consumers (Hrouga, Sbihi, and Chavallard 2022). Ultimately, recycling chain members can shirk their responsibilities. More recently, the global waste trade was dramatically changed after China banned the import of plastic waste. As a result, developed countries have to find alternative destinations to export their waste or dispose of it themselves, which has also given rise to illegal waste dumping in other countries (Wen et al. 2021).

Uncoordinated recycling chains: In general, recycling chains involve multiple stakeholders, and recycling performance can be improved through SCM perspectives, including front-end accurate waste sorting and back-end efficient recycling chain cooperation (Gong et al. 2018). Although some studies acknowledged the strategic role of recycling in SCM value enhancement (Pagell, Wu, and Murthy 2007), how to form the coordination mechanism is lacking exploration. The traditional recycling chain process is dyadic – i.e., consists of buyers and sellers of waste transactions – and ignores the valuable role of the recycling chain network (Ambilkar et al. 2022). Many manufacturers are reluctant to take on more responsibility for recycling but are forced to uphold corporate social responsibility (CSR) (Sodhi and Tang 2018). Therefore, it is urgent to understand how the value of recycling is created and, more importantly, to form a coordinated recycling chain with multiple stakeholder cooperation (Ambilkar et al. 2022; Jalali et al. 2022).

2.2 Blockchain technology potential

2.2.1 Blockchain technology essentials

Since the issuance of Bitcoin, BCT has received widespread attention. It can be defined as '*a distributed database of records or shared public/private ledgers of all digital events that have been executed and shared among blockchain participating agents'* (Saberi et al. 2019, 2118). The components include 'distributed shared ledger', 'smart contract', 'cryptography technology', and 'consensus mechanism' (Saberi et al. 2019; Wang, Han, and Beynon-Davies 2019; Dolgui et al. 2020; Pournader et al. 2020).

'Distributed' refers to the distributed storage of data in multiple independent devices (nodes), and all network members have secure information interaction without central or third-party control (Dolgui et al. 2020; Roeck, Sternberg, and Hofmann 2020). Smart contracts automatically execute scripts once the transaction meets the smart contract conditions, instead of being managed by third parties (Saberi et al. 2019; Dolgui et al. 2020). Cryptography technology is supported by digital signatures, such as hashing functions, which ensure data integrity and authenticity (Pournader et al. 2020). Each encryption key has a corresponding decryption key, and hashing enables each block to be chained into an immutable sequence (Ziolkowski, Miscione, and Schwabe 2020). The consensus mechanism is a protocol that helps the verification and transactions of different nodes in a distributed network, such as 'Proof of Work' and 'Proof of Stake' (Lumineau, Wang, and Schilke 2021). Table 1 summarises the main BCT characteristics.

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BCT characteristics are subject to different types. Based on accessibility, BCT can be simply divided into public and private blockchains (Saberi et al. 2019). The public blockchain allows all users to register and join, while the private blockchain restricts access – i.e., identity verification is required (Wang, Han, and Beynon-Davies 2019; Pournader et al. 2020). Access to the information of private blockchain is limited to selected networks and it has limited cryptographic incentives or proof-of-work (Koh, Dolgui, and Sarkis 2020; Danese, Mocellin, and Romano 2021). It is important to distinguish the BCT types before exploring actual implementations. In the recycling scenario, the various application scenarios and usage requirements correspond to different BCT types (Gong, Xie, et al. 2022).

2.2.2 Blockchain technology and recycling chain

From a general perspective, the recycling chain can be considered as a branch of sustainable supply chain management (SSCM) (Batista et al. 2019; de Lima, Seuring, and Sauer 2021; Gong, Xie, et al. 2022). The early research conducted by Pagell, Wu, and Murthy (2007) proposed the end-of-life product management of the recycling chain framework, including with and without disassembly options. Field and Sroufe (2007) proposed that the use of recycled materials can optimise operational strategies and supplier relationships across SCM structures. Gong et al. (2018) explored a packaging recycling chain from a multi-tier SSCM perspective with an emphasis on joint supply chain learning practices. Some studies analyse recycling from 'reverse logistics' perspectives (Field and Sroufe 2007; Kazemi, Modak, and Govindan 2019; Ambilkar et al. 2022) and 'closed-loop supply chain' perspective (Abbey and Guide 2018; Turken et al. 2020; Jalali et al. 2022). Also, the concept of 'circular supply chain' is rising, which integrates circular thinking and surrounding industrial and natural ecosystems into SCM (Batista et al. 2019; de Lima, Seuring, and Sauer 2021). These concepts collectively emphasise the role of 'recycling'.

More recently, such sustainable performances are expected to be achieved by the emerging 'Industry 4.0' technologies. These disruptive technologies will act as an enabler for sustainable diffusion, ultimately contributing to the triple bottom line benefits (de Lima, Seuring, and Sauer 2021; Nayernia, Bahemia, and Papagiannidis 2022). One salient trend is the role of BCT, as demonstrated by SSCM transparency and trust (Saberi et al. 2019; Bai and Sarkis 2020; Manupati et al. 2020; Tozanlı, Kongar, and Gupta 2020).

From the general SCM perspective, BCT can contribute to SCM objectives, including cost, speed, dependability, risk reduction, sustainability, and flexibility (Kshetri 2018; Pournader et al. 2020; Karakas, Acar, and Kucukaltan 2021). The essential feature of BCT-based SCM is 'decentralisation', which mitigates cumbersome centralised frameworks and asymmetric information issues (Saberi et al. 2019; Koh, Dolgui, and Sarkis 2020). Also, the immutability of BCT plays an important role in a transparent SCM. It can monitor SCM processes and construct a trust-free transparency mechanism across platforms, enabling disclosure of product information mechanism, which not only encourages integration across SCM networks, but also fosters consumer confidence (Xu et al. 2021; Shi, Yao, and Luo 2021). The BCT applications can also be extended to logistics and transport, maritime, cross-border trade, and other cases where traceability is required (Chang, Iakovou, and Shi 2020; Pournader et al. 2020; Liu, Zhang, and Zhen 2021). Another disruptive feature is the emerging governance mechanism promoted by the BCT. Specifically, BCT leads to a co-governance supply chain and reduces the role of intermediaries, which may reduce opportunistic behaviour and transaction costs (Lumineau, Wang, and Schilke 2021). It can reduce poor synchronisation which, in turn, enhances information interaction and trust among participants (Dubey et al. 2020; Zhu, Kouhizadeh, and Sarkis 2022).

Also, BCT shows great potential for circular economy and sustainability. Kouhizadeh, Zhu, and Sarkis (2020) proposed that BCT can transform and advance circular economy in terms of regenerate, share, optimise, loop, virtualise and exchange dimensions. Saberi et al. (2019) conceptualised BCT application in SSCM in terms of economic, environmental, and social dimensions. Specifically, the enhanced visibility and transparency by BCT enable the monitoring of SSCM performance across multi-echelons, e.g. the information synchronisation of carbon emissions (Manupati et al. 2020). BCT can be used as an effective information governance tool to support the realisation of rationalised product portfolios, e.g. the embracement of product deletion to streamline manufacturing for greater agility and waste reduction (Zhu, Kouhizadeh, and Sarkis 2022). Additionally, by combing efficient data collection with digital devices, BCT can confidentially record the complete data timestamp from raw material to retail, and eventually to material recovery, facilitating the formation of innovative 'disassembly-to-order' systems (Tozanlı, Kongar, and Gupta 2020). Furthermore, Esmaeilian et al. (2020) proposed future directions of BCT for SSCM, including incentive mechanisms of tokenisation, product life cycle visibility, system efficiency, and sustainability performance monitoring and reporting.

In recycling, França et al. (2020) studied how BCT can benefit sustainable development goals (SDGs) in solid waste management. It shows a reward system by providing cryptocurrencies to encourage residents to participate in the exchange of recyclables, and the virtual coins can be used to exchange cash and purchase goods. Chidepatil et al. (2020) explored the combination of BCT and artificial intelligence to tackle plastic waste, where artificial intelligence can effectively improve waste segregation and BCT serves as a trust-based platform for securing information with traceability. Some studies focus on specific recycling types, such as packaging waste

(Ajwani-Ramchandani et al. 2021), marine debris (Howson 2020; Gong, Wang, et al. 2022), and electronic waste (Sahoo, Mukherjee, and Halder 2021).

In general, BCT research on the recycling chain is emerging. Since it involves multidiscipline topics, most literature appears scattered with the broader concepts of circular economy and SSCM. Some emerging literature has focused on BCT as a possible solution, but most research in this domain does not provide a thorough analysis of practical implementations and performance.

3 Methodology

To comprehensively review relevant studies, we drew on the research methodology of existing BCT-related literature review articles (Pournader et al. 2020; Karakas, Acar, and Kucukaltan 2021; Liu, Zhang, and Zhen 2021; Ghadge et al. 2022). In addition to conducting a thorough review of relevant studies, this study also aims to propose a novel conceptual framework via a content-based review method to answer the research question: *How can BCT be applied in recycling chains?* As a branch of the systematic literature review method (Tranfield, Denyer, and Smart 2003), the content-based method has been widely adopted in SCM studies (Seuring and Gold 2012; Kazemi, Modak, and Govindan 2019; Pournader et al. 2020). It involves rigorous and orderly approaches to consolidate and identify gaps in existing literature in a transparent and scientific manner as Figure 1 shows.

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In the material collection stage, we adopted a dual and pragmatic approach to collect two types of source material – *academic* and *grey* literature. The main academic literature search is filtered in the database by search strings that have been developed and refined over several iterations (Pournader et al. 2020; Li, Lee, and Gharehgozli 2021; Shi, Yao, and Luo 2021). We selected three databases – Scopus, Web of Science and EBSCO - which are the most reliable databases with multidisciplinary and broad coverage (Adams, Smart, and Huff 2017; Pournader et al. 2020). The three databases also allow for the selection of source types (articles and conference papers) to aid subsequent analysis. The search string needs to be sufficiently broad to answer the research question but also specific enough for targeted research objectives. Given the two categories, 'blockchain' and 'recycling', we identified commonly used search strings from previous BCT-related literature review journal papers (Pournader et al. 2020; Karakas, Acar, and Kucukaltan 2021; Shi, Yao, and Luo 2021; Ghadge et al. 2022), and selected the following recycling-related strings:

- 'Blockchain' related: ('blockchain' OR 'distributed ledger' OR 'smart contract')
- 'Recycling' related: ('recyc*' OR 'waste management' OR 'municipal waste' OR 'solid waste' OR 'plastic')

The search strings were adopted in the three databases within the title, abstract and keywords, and the time frame was set as June 2022 without a starting year. The search generated 468 papers from the three databases. The initial screening removed duplicate papers, followed by the date (up to June 2022), document category (journal articles and conference papers), and language filters (English only), which left 186 items. Then, we performed an abstract analysis to identify whether the items fell within the context of BCT and recycling and filtered to 85 items.

Next, the full-text assessment was strictly applied according to inclusion and exclusion criteria (Table 2). In general, the essential inclusion criterion was that selected items can contribute to the research question – i.e., explain the BCT application in recycling chains. Items are selected based on relevance rather than quality bias, which follows the notion of 'fit-for-purpose' suggested by Adams, Smart, and Huff (2017). However, the selected items should focus specifically on the BCT application in the recycling sector, so some articles from a broader level were excluded. Specifically, studies generally explored the BCT application in sustainability, as well as studies on general circular economy considerations, e.g. remanufacturing and product deletion were also excluded (Bai and Sarkis 2020; Manupati et al. 2020; Zhu, Kouhizadeh, and Sarkis 2022). For example, Kouhizadeh, Zhu, and Sarkis (2020) explored the practice of BCT in circular economy through 10 case studies, which involved recycling to some extent. However, the main unit of analysis was the circular economy, so their study was excluded. Similarly, articles that explored other technological solutions, or collectively referred to 'Industry 4.0' technologies were excluded, although some sections mentioned BCT, e.g. (Wang and Wang 2019; Nayernia, Bahemia, and Papagiannidis 2022). Also, this study adopts a SCM perspective, which mainly focuses on the management subject while other disciplines such as environmental engineering and computer science were excluded. As a result, 38 academic items were selected for further analysis.

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Additionally, a complementary strategy was employed to search grey literature. Because current research is lagging behind applications, grey literature can provide contemporary and contextually relevant information, and addresses the publication time lag that may exist in journal articles (Adams, Smart, and Huff 2017). More importantly, it can reflect practical application examples, which may not be involved in the scientific literature (de Lima, Seuring, and Sauer 2021). Following the grey literature categories set out by Adams, Smart, and Huff (2017), we only selected those publications with significant retrievability and credibility.

Specifically, we conducted a manual search of the literature via Google to locate real business cases. To maintain consistency, we used the same search strings that were applied in the scientific literature searches. This approach generated a total of 13 pages, and we retrieved and read all Google hits results. Considering the potential quality bias, we excluded blogs, news, and tweets, and only business reports that gave full illustrations of real-world applications rather than general descriptions were selected. To increase credibility, we included reports published by authoritative third-party institutions rather than internal publications – e.g., white papers – and four reports met the criteria. Combining the scientific and grey literature search, we retrieved items in total 42. Then, following the complementary search through snowballing (retrieve the reference list from selected items), we added three items, bringing the final number to 45 as Figure 2 shows. Appendix 1 summarises the selected items.

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In the data analysis, we adopted systematic integration and analytic categories pattern by thematic analysis (Seuring and Gold 2012; Sodhi and Tang 2018). The analytic categories include: 'BCT application functions in recycling', 'BCT limitations in recycling functions', and 'Recycling chain performance by BCT application'. Following the abductive reasoning for theory development from Seuring et al. (2020), this research generates the final conceptual framework based on the 'Stimulus, Response and Performance' framework proposed by Reuter et al. (2010). This framework helps us to follow the logic that waste crisis drives innovative recycling solutions, and it can explore the adaptive behaviour of BCT applications and potential performance in the adoption process. Specifically, the abductive approach is for 'theory modification', which means it starts from existing theoretical frameworks, adding new concepts or developing via an abductive process (Seuring et al. 2020).

4. Descriptive summary

This section presents the descriptive summary of selected items, including publication trends and sources, methodology, geographical distribution, and waste type focus. In general, the literature is widely distributed, with variable quality and maturity levels, which reflects that current research is still in the initial stage.

The selected journal papers were published from 2018 onwards. Before 2018, there were no publications in this area. Since 2018, with the increasing interest in BCT and SCM, some researchers began to focus on recycling as a branch of SSCM. The publication trend illustrates a growing research interest in BCT interfacing recycling chains. Figure 3 presents the publication trend of the selected 35 journal articles.

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Of the selected papers, a widely distributed and immature feature emerges. Twenty journals provide only one article, and four journals provide more than two papers. These four journals are *Resource, Conservation & Recycling, Journal of Cleaner Production, IEEE Access,* and *Waste Management*. Also, selected items show a diverse quality distribution according to the Academic Journal Guide 2021. Only 34% of the selected articles were from the ABS journal list as Figure 4 shows. Only five papers came from 3* rated and five 2* rated journals, which also shows a diverse and immature feature.

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Next, Figure 5 shows the research methodologies applied to selected items. We followed the five-research type classification from (de Lima, Seuring, and Sauer 2021).

These types are conceptual, case study, survey, modelling, and review. Therein, conceptual articles are by far the main research type, accounting for nearly 43%. The dominant number of conceptual articles suggests that the field is in a state of reasoning, reflecting the fact that BCT in recycling is still in the exploratory phase and the technology is immature in its use. The case study approach and review type together account for 46% of the total. Empirical studies further contribute to the refinement of theoretical concepts, while review articles help to sort out conceptual constructions to form theoretical conceptual development. The other category is modelling, with only four articles, indicating that researchers are trying to adopt new theoretical tests and develop methods to enrich the field.

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Next, Figure 6 shows the geographical distribution of the selected articles. It shows that the majority come from the UK, India, China and the USA. This could explain the relatively mature use of BCT technology in these regions and the widespread interest in recycling research and practices. Also, Figure 7 demonstrates the BCT application to a wide range of waste types (overall 12 types), which shows the rich potential. Due to the dominance of conceptual articles, most articles explore the issue from a general perspective rather than focusing on a specific category, while plastic, municipal solid waste, and electronic waste received higher attention.

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In terms of other types of documents, five conference articles, four reports, and one teaching case met the inclusion criteria. In addition to providing conceptual constructs, they illustrate a wealth of practical examples that can complement the scientific literature.

Similar to the trend of scientific literature, the earliest publication in the grey literature was in 2018, which again demonstrates that the field is still in the early stages of research.

5. Thematic analysis

This section presents the findings via thematic analysis. Thematic analysis is widely used in qualitative data analysis, through the comprehensive integration of text data to define and form themes (Sodhi and Tang 2018; Hastig and Sodhi 2020). Potential themes are derived from three categories: 'Functions of BCT in recycling functions', 'BCT feasibility limitations in recycling chains' and 'Recycling chain performance with BCT application'. Specifically, the latter two categories are abductively drawn from the Technical-Organisational-Environmental (TOE) framework (Tornatzky, Fleischer, and Chakrabarti 1990) and the BCT-based SCM objective framework from Kshetri (2018) respectively. Sub-themes of each analytic category are inductively integrated by the coding procedure. The definition of themes and sub-themes are iteratively confirmed among the co-authors.

5.1 Functions of blockchain technology in recycling chains

Based on the selected literature and coding procedures, BCT-based recycling functions are summarised into four themes as Figure 8 shows.

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5.1.1 Transparency

Waste data/ information integrity

BCT ensures immutable information. Through the encryption function, recycling flows will be stored in an immutable way and the selected BCT version determines the access permissions of users (Ongena et al. 2018; Júnior et al. 2022). Supplemented by lifecycle assessment of the waste tracking basis, the BCT-based waste system can conduct waste flow analysis for waste auditing (Centobelli et al. 2022; Samadhiya et al. 2022). Also, members can share and verify recycling data to ensure continuity and flexibility. Furthermore, the BCT-based platform can address the lack of trust scenario caused by the original information asymmetry and combat illegal dumping of cross-border waste transactions (Schmelz et al. 2019).

Specifically, BCT-based data integrity is achieved by immutable data feeding and reading. In the SCM scenario, material and information flows are considered as transactions, and each process has a unique transaction ID, which will be stored in the 'distributed ledger'. In terms of data feeding, physical data is transferred into the BCT system in a standard way containing critical material and activity information. In contrast to data feeding, data reading refers to identifying and reading information from the system (Danese, Mocellin, and Romano 2021). Data is compressed into standard digital packages (forming blocks) and stored in the BCT system. Each new transaction forms a new block that contains all previous transactions ensuring immutability and allowing digital tracking (Saberi et al. 2019). In practice, physical products and digital information are usually transmitted via scanning digital tags.

Take plastic recycling as an example, in the case where all recycling chain members are linked via the BCT platform, the plastics collector is given login access to the BCT platform and enters key information (which is mutually designed by members or trusted coordinators according to the BCT version) such as data registration information, activity date, location, material, facility, testing information, batch number, and certification documents. This information is then stored in the form of data packages (or blocks). Subsequently, the next stage stakeholder, e.g., the recycling company, access this information and enters the new activity data. Ultimately, all transaction information from each link in the supply chain is recorded in the BCT system, which is readable and stored by the encrypted security of BCT forming the chain of custody standardisation (Centobelli et al. 2022). To enhance the authenticity of data entry and to prevent 'garbage in, garbage out' situations, data validators can be added to ensure the accuracy of data feeding (Danese, Mocellin, and Romano 2021).

Waste traceability

BCT provides traceability for recycling chains thanks to data integrity (Saberi et al. 2019). The tracking feature can record material and information flows throughout the whole process, which can enhance overall transparency. A common practice is to digitise each batch by attaching digital tags, and recycling chain members can update the digital twin to reflect the latest changes at different stages (Chaudhuri, Subramanian, and Dora 2022). Specifically, BCT can create a virtual digital twin for each batch of material, and this batch can be tracked throughout entire recycling chains. Meanwhile, the digital twin contains relevant information such as product original and content, date, process, and carbon footprint for each batch (Wang and Wang 2019; Alves et al. 2022).

Studies show that this unique traceability can be applied to diversified waste types (see Figure 7). For example, Chidepatil et al. (2020) reported that BCT and multi-sensor-driven technology could segregate plastic waste and track the lifecycle more transparently. Ajwani-Ramchandani et al. (2021) proposed a BCT-based circular economy framework for packaging waste. Similar logic includes industrial wastewater (Hakak et al. 2020), hazardous waste management systems (Hrouga, Sbihi, and Chavallard 2022; Song et al. 2022), medical waste (Ahmad, Salah, Jayaraman, Yaqoob, Omar, et al. 2021; Kassou et al. 2021; Bamakan, Malekinejad, and Ziaeian 2022), electronic waste (Sahoo and Halder 2020), household waste (Gong et al. 2021). , marine waste (Howson 2020; Gong, Wang, et al. 2022), textile waste (Alves et al. 2022; Chaudhuri, Subramanian, and Dora 2022), construction waste (Voorter and Koolen 2021), and municipal waste management (França et al. 2020; Damadi and Namjoo 2021; Kahya et al. 2021).

Waste accountability

The waste accountability function serves as a by-product of data integrity and traceability. The BCT-based system can record information on waste flows, including ownership information of waste generation (Júnior et al. 2022). This solution offers great potential for the EPR system. The traditional EPR system elaborated on the principle of 'who produces, who pays'. It claims that the main responsibility lies with the manufacturers, who then claim higher manufacturing costs, and retailers also increase selling prices accordingly. Ultimately, the recycling responsibility is attached to consumers (Li et al. 2017). However, the effect of EPR is unclear and it is difficult to track and confer responsibility to different stakeholders in its implementation. The transparency, accuracy, and security required by EPR can be improved by BCT implementations. Specifically, BCT can clarify waste ownership responsibilities and form a trust-free supervision mechanism. Also, smart contracts based on the ability to define clear responsibilities and ownership can guide producers to fulfil their responsibilities (Akbarieh et al. 2020).

5.1.2 Integration

Multi-party coordination

BCT is suitable for multi-party collaboration, particularly for various participants involved in recycling chains. Traditionally, fragmented recycling networks caused chaos in recycling markets (Pagell, Wu, and Murthy 2007). By contrast, transparent information exchange by BCT promotes the integration of the recycling chain without the risk of counterfeiting (Ongena et al. 2018). Recycling chain members have access to the on-chain data of each transaction information. Companies used to declare their recycling practices that can be verified and monitored by auditors. However, such an untrusted approach does not allow for real-time monitoring and information interaction among members. Secure storage of data on the blockchain and accessibility for all members help to achieve self-validation of members as any misdirected data can cause subsequent disruptions (Saberi et al. 2019). Also, peer-to-peer security information sharing and networking benefits can motivate members to collaborate (Steenmans, Taylor, and Steenmans 2021). This achieves networking effects: residents obtain reward tokens by recycling participation, recyclers improve recycling chain transparency, and manufacturers can show product lifecycles for CSR (Gong, Xie, et al. 2022).

Social inclusion

Social inclusion refers to engaging informal sectors to achieve SDGs. In developing countries, these informal groups (e.g., WPs) have been operating in poor working environments, and, more often than not, have been unrecognised (Ajwani-Ramchandani et al. 2021). With the expansion of urbanisation, these 'marginal groups' gradually disappear because they have less ability to work competitively (Peshkam 2019). The incentive scheme provided by BCT can attract participation from street WPs, i.e., provide them with digital identities, recognising their waste collection activities. In the past, these WPs made a living by selling the waste they collected, but the amount they collected and the payment they received were subject to market fluctuations. The BCT-based network encourages WPs' participation as they can obtain stable incomes with fair wages and work conditions and gain recognised identities by joining recycling activities in an official approach (Gong, Xie, et al. 2022). In addition, governments could also manage this traditional informal sector more efficiently and effectively.

5.1.3 Behaviour channelisation

Recycling rewarding

Recycling is inseparable from participation, and tokenisation proposes rewarding incentives for residents (França et al. 2020). Residents who collect waste can receive corresponding tokens or redeem coupons (Climate 2020; Lenz 2021). The issued tokens will be recorded into digital accounts and uploaded to the BCT system in an immutable manner (Damadi and Namjoo 2021). Some organisations designed tokens that can be used for physical consumption, public services, or directly exchanged for cash (Lenz 2021). Furthermore, the crypto credit function also shows the potential of green investment, such as encrypted points for carbon footprint certificates (Katz 2019). With the global emphasis on carbon neutrality, BCT offers rewarding potential for recycling stakeholders such as collectors (Gopalakrishnan and Ramaguru 2019), and for recyclers who conduct recycling practices to reduce carbon emissions (Morrow and Zarrebini 2019).

Recycling supervision

BCT forms a 'co-governance' mechanism, which is conducive to achieving mutual supervision among members (Esmaeilian et al. 2020). Traditional recycling is supervised by municipal departments and coordinated with associations such as the producer responsibility organisation. BCT can link recycling chain members into interconnected networks, where recycling processes are visualised (Khadke et al. 2021), although different stakeholders need to be responsible for corresponding links. Also, the BCT network can assign penalties for non-compliance (Gong et al. 2021). . The transparent audit function can restrict members to comply with environmental permits and punish improper behaviour (Liu et al. 2020). However, a fair audit mechanism should be designed in practical implementations.

5.1.4 Service transformation

Strategic consideration

For enterprises, BCT applications can be a strategic consideration, particularly in the rise of sustainable concepts (e.g., 'circular economy', 'carbon neutrality') and the promotion of digital service transformation (Chaudhuri, Subramanian, and Dora 2022). Manufacturers may be forced either by external stakeholder pressures or internal pursuit of sustainability, to embrace the concept of end-of-life management and build the CSR reputation (Sodhi and Tang 2018; Ambilkar et al. 2022), while retailers are willing to present product journey information to increase consumer trust and potential price premium. In general, sustainability can be used for brand publicity although some criticise the 'gimmick' nature or greenwashing purposes (Howson 2020).

Recycling process optimisation

Waste management expenditure is still an important part of municipal budgets; even in developing countries, it accounted for more than 20% of the budget (Kaza et al. 2018). From the managerial level, BCT shows process optimisation potential, i.e., removes irrelevant or untrusted third-party supervision (Gong et al. 2021). In the collection phase, BCT can combine with artificial intelligence technology to realise automatic segregation (Chidepatil et al. 2020). The digital recycling chain reduces the traditional paperwork as recorded data will be encrypted, and municipal departments can verify the authenticity of information with less fraud (França et al. 2020). Also, the BCT platform can optimise transportation routes with a global positioning system, thereby reducing logistics costs (Gong, Xie, et al. 2022).

Table 3 summarises the overview indicators for the functions of BCT application in the recycling chain.

--- Insert Table 3 about Here ---

5.2 Blockchain technology feasibility limitations in recycling chains

Considering the fragmented nature of feasibility limitations, the study uses the TOE framework to integrate evidence coherently, which serves as one prestigious and widely used comprehensive framework (Clohessy and Acton 2019). Technological refers to the technical characteristics of BCT, such as complexity and adaptability, and comparisons with existing technologies. The feasibility limitations include effects from endogenous and exogenous factors. The organisational aspect as an endogenous factor can explain adoption behaviour and further scale-up considerations, including manager support, stakeholder acceptance, and organisation size (Tornatzky, Fleischer, and Chakrabarti 1990). Also, BCT applications need to consider external factors (beyond the boundaries of companies), including other recycling chain members and the overall macro environment (Kouhizadeh, Saberi, and Sarkis 2021). Figure 9 summarises the limitations of BCT in recycling under the TOE framework.

--- Insert Figure 9 about Here ---

5.2.1 Technical dimension

Immutability/recording adverseness

Immutability can be a double-edged sword. After inputting data in a BCT environment, subsequent editing and modification are not feasible, and any erroneous data would also be recorded permanently (Taylor, Steenmans, and Steenmans 2020). For example, when the recycling information, such as weight, is recorded incorrectly in the collection stage, there will be cascading effects on subsequent processing. Thus, it is essential to ensure correct data input, such as the use of sensors to collect objective data to avoid the 'garbage in, garbage out' problem (Ongena et al. 2018).

The ambiguous ownership clarification issue still exists. Theoretically, BCT records complete waste processes of entire waste streams. Waste is usually identified via digital identities – for example, quick response codes – but it is infeasible to read when waste is separated or broken (Taylor, Steenmans, and Steenmans 2020). In practice, one single batch of waste may be identified repeatedly at different life cycle stages, which may confuse data recording. Therefore, BCT records do not radically solve the waste ownership issue, particularly for mixed waste, which affects waste flow transfer (Ahmad, Salah, Jayaraman, Yaqoob, and Omar 2021).

Privacy issue

The dismantling process and transparent display would inevitably cause privacy issues. When recyclers conduct disassembly processes, details of various components from products will be disclosed, particularly for those products with higher values (Chen and Ogunseitan 2021). Also, recycling chain members may not wish to be over-transparent. In household waste, residents do not disclose what products they consume and how much waste they ‘contribute’. Further, those recyclers with special recycling patents are unwilling to show their complete recycling processes. More importantly, price information may be sensitive as it may disrupt the original waste transactions market (Gong et al. 2021).

Inherent design flaws

Technically, the distributed ledger needs to record and verify a large number of transactions, which inevitably causes storage problems (Saberi et al. 2019). Also, BCT is less flexible to change given the smart contracts, which may not be able to cope with the fast-changing business environment requirements; for example, adjustment of recycling policies (Ongena et al. 2018). Compared to other traditional databases, the huge energy consumption involved in BCT was widely criticised (Esmaeilian et al. 2020). Although the essential goal is to improve recycling performance, excessive energy consumption seems to contradict the pursued sustainability concept (Saberi, Kouhizadeh, and Sarkis 2018).

Immature blockchain technology

BCT is still in the development stage with limited application, low scalability, and technology hype suspicion (Saberi, Kouhizadeh, and Sarkis 2018). In practice, most BCT practices are pilot projects with slow adoption. The scalability issue of platform interoperability needs to be solved. Also, actual implementations need to be further confirmed since some functions may be over-idealised or can even be achieved by other existing solutions. For example, Internet-based recycling solutions also provide data visibility among waste flows (Tong, Tao, and Lifset 2018).

5.2.2 Organisational dimension

Organisational readiness

Organisational readiness refers to organisational resources available to adopt new technologies, such as human resources, finance, and organisational capabilities (Clohessy and Acton 2019). First, the construction of the BCT platform could be expensive. The current BCT applications are mainly piloted by multinational companies such as Maersk and Walmart (Kshetri 2018), while these may pose a huge burden for small-scale recycling companies. Also, organisations may lack sophisticated experts because BCT application in recycling is still in the early stages (Liu, Zhang, and Medda 2021). Second, BCT applications require ‘digital bones’ (e.g., digitalisation foundation) since they usually rely on existing technology layers whilst it has been generally recognised that the recycling industry has a low digitalisation adoption rate (Chidepatil et al. 2020).

Stakeholder acceptance

Although the recycling industry is experiencing ongoing ‘digitisation’ with the concept of ‘smart waste management’, the acceptance level of BCT is unknown. Kouhizadeh, Saberi, and Sarkis (2021) claimed that low availability at the user level is the key weakness. Particularly, BCT can be extremely challenging for informal recycling personnel who only have limited BCT understanding. Also, there are conflicting issues around benefits allocation since the business requirement of BCT stakeholders can be different (Gong et al. 2021). Also, leadership questions for reaching consensus – i.e., the role that recycling companies play as initiators or controllers – should be considered (Lumineau, Wang, and Schilke 2021).

Stakeholder commitment

It is difficult to coordinate stakeholders within a fair framework to reach long-term commitment (Gong, Xie, et al. 2022). Multi-stakeholders have inconsistent BCT perceptions, which may lead to conflicts in value distributions. For example, the ultimate benefit of the BCT application is to serve entire recycling chains while the expectations of different stakeholders are unknown (Gong et al. 2021). The following consideration will be the BCT version (public, private, or consortium) selection because the type of selection determines data access rights and the accompanying governance mechanism (Ongena et al. 2018). Furthermore, technical privacy issues will affect information sharing and the commitment of stakeholders. Recyclers are reluctant to be excessively transparent because this may disrupt their existing recycling business.

5.2.3 Environmental dimension

Recycling chain compatibility (internal)

The (internal) recycling chain environmental aspect refers to the context between recycling chain members – i.e., outside the boundaries of focal companies but at the recycling chain level. First, the BCT solution provides unclear responsibility divisions, which causes compatibility issues (Ahmad, Salah, Jayaraman, Yaqoob, Omar, et al. 2021). BCT emphasises the ‘co-governance’ mechanism, but it fails to clarify the definition and boundaries of responsibility (Taylor, Steenmans, and Steenmans 2020). Second, it is important to consider how to encourage members to form an incentive mechanism. The rewarding mechanism encourages participation, but stakeholders may not participate spontaneously (Taylor, Steenmans, and Steenmans 2020). Meanwhile, the rationality of rewarding and punishment system design should be carefully designed because it may discourage participation.

Industry constraint (external)

The industry constraint (external) aspect includes market dynamics, lack of policy, and low industry participation (Kouhizadeh, Saberi, and Sarkis 2021). The market dynamics are reflected in recycling industry fluctuations and BCT application competitions. For waste types, such as plastics, manufacturers may wish to use virgin polymers based on petrochemical feedstock because the market price of recycled plastics is sometimes even higher. The rise of smart waste management does not mean that BCT alone can be the panacea; other feasible solutions are also emerging, such as the Internet-based mode (Tong, Tao, and Lifset 2018).

Additionally, there are no corresponding legal frameworks for BCT applications (Howson, 2020). It is also difficult to establish a standard recycling mode according to localisation issues (Esmaeilian et al. 2020). Even for the European Union, which has relatively complete regulations, the EPR implementations are not consistent and are hard to embed with BCT applications. For developing countries, corresponding accountability mechanisms and waste management regulations are even more lagging.

Table 4 summarises the indicators for the BCT feasibility limitations in the recycling chain.

--- Insert Table 4 about Here ---

5.3 Recycling chain performance with blockchain technology application

Kshetri (2018) explored the BCT's roles in meeting key SCM objectives in 11 case studies. Based on this research, we summarised that the BCT application enhances recycling performance in terms of cost, dependability, flexibility, sustainability, and risk reduction, as shown in Table 5. As a branch of SSCM, this framework helps to explain the role of the BCT-driven recycling chain and integrates potential performances.

--- Insert Table 5 about Here ---

Cost

The principles of decentralisation aim to minimise the supervision of central entities or third parties. The traditional approach is to review recycling indicators through third-party agencies such as audit institutions. After the BCT application, the supervision mechanism by third-party intermediaries will be minimised and less manual supervision and paperwork records (Gopalakrishnan, Hall, and Behdad 2021). Also, the BCT solution is expected to minimise operating costs. The common solution is to combine BCT with the Internet of Things, and artificial intelligence to improve waste segregation (Peshkam 2019). Wang, Ma, and Hu (2022) showed that the introduction of BCT is beneficial in improving the actual recycling rate of electronic waste and reducing the marginal cost of waste platforms. Also, it is expected to reduce transportation and management costs with efficient sorting, transportation, and information transmission in recycling (Gong, Xie, et al. 2022).

Dependability

Dependability is reflected in recycling chain accountability. With BCT implementation, recycling behaviour will be constrained either by internal stakeholder requirements or external pressure. Members are required to perform according to smart contracts by setting specific encouragement or punishment measures (Taylor, Steenmans, and Steenmans 2020). Also, BCT can build reliable credit systems. All recycling records including waste material flows will be recorded, each member has trusted identity authentication, and the immutability mechanism maintains data integrity (Esmaeilian et al. 2020). Traditional performance criteria such as recycling rate and participation rate are usually drawn from companies' self-report and are then audited by third parties. However, it has been criticised for not being transparent and the authenticity of its indicators has been questioned. Conversely, the BCT system can establish trust-free measurement (e.g., issue digital certification).

Flexibility

Flexibility is reflected in the 'networking effect' and in the convenience of the recycling process. Compared to traditional modes, networking effects via multi-party coordination can lead to stakeholder cooperation and information sharing (Gong, Xie, et al. 2022). These provide mutual benefits to members – for example, recyclers achieve efficient resource utilisation, the government reduces municipal waste management costs, and residents earn recycling rewards. On the other hand, flexibility is reflected by speeding recycling chain processes. BCT can automatically track and immediately record recycling processes, connecting with different stages and identifying irregularities. Manufacturers can show the product life cycle journey while consumers can verify product recyclability (Liu et al. 2020). Also, BCT digitalises recycling chains with simplified procedures (e.g., eliminating traditional paper recording), and improves the time-consuming processes in the collection and separation stages (Chaudhary et al. 2021).

Sustainability

BCT helps to achieve triple bottom line performance (Saberi et al. 2019). *Environmentally*, BCT helps to protect the ecological environment as collected waste will prevent the waste from flowing into landfills or the ocean (Howson 2020). *Social*ly, it is conducive to achieving SDGs by engaging informal WPs (Gong, Xie, et al. 2022).

Compared with previous street collections, WPs are more willing to participate in BCT-guided activities because they can earn stable living wages and gain access to public services (Ajwani-Ramchandani et al. 2021). *Economically*, BCT promotes innovative business explorations. It creates high resource utilisation and profitable circular business models (França et al. 2020), as well as the 'private-public' model by cooperating with the government (Gong et al. 2021). The following consideration. Moreover, Lenz (2021) proposed that the BCT solution can kindle entrepreneurship for recyclers.

Risk reduction

Risk reduction is reflected in solving information asymmetry. Immutable and transparent mechanisms can prevent fraud and malicious tampering since any modifications will be notified (França et al. 2020). Also, BCT helps to supervise the recycling market (Howson 2020). Traditionally, there is significant information asymmetry between buyers and sellers and developing countries mainly adopt cash transactions (collect waste and then sell to recyclers) while the token solution can enhance transaction security (Zhang 2019). More importantly, BCT helps local governments to tackle smuggling trade and taxation issues. It can combat non-compliance over the treatment of waste disposal and illegal dumping to form fair recycling businesses, particularly following the waste import ban issued by China (Wen et al. 2021).

6. Discussion

Based on the review findings and the '*Stimulus, Response and Performance*' model from (Reuter et al. 2010), we propose a conceptual framework of BCT application in the recycling chain as shown in Figure 10. Reuter et al. (2010) explained the adaptive behaviour of focal companies to consider sustainable supplier management with dynamic capability views. Similarly, in the BCT application, the *triggers/stimuli* refer to those factors which drive new solutions to tackle the waste crisis. This model can explain the logic flow of BCT adoption in recycling (why use BCT) and demonstrate the dynamic trajectories (how BCT can be applied). In general, the existing chaotic recycling status promotes further solution explorations while digitalisation provides innovative potential. The emerging solution is the BCT application, which may potentially tackle the recycling crisis. However, the BCT application is not a panacea as it must consider essential *determinants* before rolling out the initiative. The potential performance improvement of the BCT can only be realised under certain circumstances and be mitigated by *performance uncertainties*.

--- Insert Figure 10 about Here ---

The looming waste crisis is exacerbating the current chaotic waste state and the appalling waste generation figures spurred urgent exploration of emerging solutions. The 'stimulus' of seeking new solutions drives innovation adoptions. One existing solution is the 'Internet recycling' mode – i.e., embracing the 'Internet' concept to build an online marketplace for waste trading (Tong, Tao, and Lifset 2018). It combines online and offline methods (e-commerce) and credit-redeem rewards to encourage waste trade. However, as a lucrative behaviour, it cannot offer sufficient incentives to encourage participation or form recycling chain coordination. Also, existing smart waste management solutions are mainly applicable for high-value recyclables, such as electronic products, while low-value types (e.g., bottles, multilayer composite packaging) seem to be overlooked to a great extent. These limitations trigger further exploration.

The potential 'response' is BCT application driven by the 'Industry 4.0' promotion, which is considered as the game-changer (Ongena et al. 2018). Focal companies may learn about the BCT-rich functions, such as disruptive creativity in circular economy (Kouhizadeh, Zhu, and Sarkis 2020). These solutions may inspire their enthusiasm and lead to 'spill-over effects' in other sectors, generating perceptions of the usefulness of BCT. Leading pioneer companies such as *Plastic Bank* and *Empower* kicked off BCT exploration, which further stimulated practical explorations (Gong, Xie, et al. 2022). Thus, the demand for innovative solutions in waste management and the potential provided by BCT constitute the '*stimuli*'. Thereby, the following proposition is formulated:

Proposition 1: *Chaotic waste management stimulates the need for* innovative *solutions while BCT is considered as the game-changer.*

The BCT application initiators can be any recycling chain members who are equipped with sufficient capabilities (determinants), and the TOE framework is referenced to demonstrate adoption capabilities. According to the TOE lens, the 'technological' level includes the characteristics and applicability of the technology (Tornatzky, Fleischer, and Chakrabarti 1990).

The BCT application scenarios are designed according to corresponding technical characteristics. The tokenisation feature is used to motivate participants, traceability is conducive to tackling waste flow tracking, and the decentralised feature is used to form a co-governance mechanism (Esmaeilian et al. 2020). The adoption of any functions should start from specific commercial demands (e.g., tackling recycling bottlenecks) rather than vague assumptions. For example, as one of the functions, transparency appears to be effective, but it is necessary to clarify who needs it and how data visibility can be ensured. Specifically, the demand for this function varies among different stakeholders. Potentially, municipal administrations may need transparent recycling flows to strengthen supervision; or manufacturers may need to prove product information or social responsibility to consumers (Steenmans, Taylor, and Steenmans 2021). However, the enthusiasm among waste collectors is limited since they do not take charge of processing and circulation of the back end, and traceability cannot radically transform their business models. Therefore,

Proposition 2a: *Technical characteristics and availabilities of BCT influence the adoption in the recycling chain as it must serve specific application scenarios*.

When the application scenario fits with the initiators' expectations, the further step is to consider organisational factors – i.e., structure, resources, networks, and commitment of focal companies (Tornatzky, Fleischer, and Chakrabarti 1990). Common organisational capabilities encompass financial resources and human resources (Clohessy and Acton 2019). The fact is that current BCT pilots are initiated by large companies with strong financial support and technical talents (Kshetri 2018). For recycling companies, particularly small- and medium-sized enterprises, the lack of resources is a crucial challenge (Saberi et al. 2019). Also, organisational culture and top manager commitment affect long-term commitment. Some managers may lack an understanding of BCT and thus may be reluctant to roll it out (Gong, Xie, et al. 2022). For companies that tend to adopt incremental innovation strategies, the scale-up would be slow as they may wait and see how other pioneers benefit from it. Therefore, this generates the organisational aspect proposition:

Proposition 2b: O*rganisational capabilities are an important internal factor not only affecting the decision-making of BCT adoption but also determining subsequent scale-up exploration.*

'Environmental' is an external factor, including market dynamics, industry interdependence, and regulatory support (Clohessy and Acton 2019). As discussed in section 5.2.3, it can be divided into recycling chain-based (internal) and external lenses.

BCT-based recycling chains require coordination with multiple members, but privacy issues may hinder further coordination. Recyclers may be unwilling to disclose the price that they charge the processing companies, who may not expect complete transparency either. Engaging in the informal sector can also be challenging considering the low level of education and complex localisation issues. In other words, the BCT initiative will reconstruct existing recycling chains and the participation of recycling chain members is crucial. In terms of 'broader external context', it is mainly affected by laggard regulatory policies and market competition. The legal framework related to BCT is still in the infancy stage (Saberi, Kouhizadeh, and Sarkis 2018), and market competition may favour other mature solutions such as the Internet-based recycling mode waste trading (Tong, Tao, and Lifset 2018). Therefore:

Proposition 2c: *Environmental factors as external conditions affect the BCT adoption decision. The willingness for BCT application will be higher when environmental conditions are in place.*

Subsequently, it is imperative to contemplate the evaluation of performance improvement and feasibility limitations. The critical benefit of deploying BCT is accessible information for recycling chain members. Traditionally, the lack of information and visualisation causes the 'chain liability effect' in supply chain traceability, such as product counterfeiting, lack of ethical production and greenwashing scandals (Hastig and Sodhi 2020). People can only access information from statements of companies or third-party institutions, but these have not improved supply chain transparency or eradicated mistrust. Based on the technical settings of the BCT version, BCT offers a disruptive approach to data visualisation and traceability.

Each activity has an exclusive digital identity on BCT and digital tags link to products and information, which is entered at the origin of the transaction (Danese, Mocellin, and Romano 2021). As a result, suppliers increase the level of trust in sharing information due to inherent immutable settings, while consumers and even supervision bodies can access relevant information for supervision purposes (Lumineau, Wang, and Schilke 2021). A popular application is the use of BCT to verify recycled fabrics adopted by the fast fashion industry. Brands claim products are made from recycled materials and BCT provides consumers with full traceability information. Through scanning digital tags, consumers can access production journey information and even obtain the carbon footprint information of brands' sustainability efforts (Alves et al. 2022).

However, the achievement of these objective performances depends on specific conditions. For example, the pursuit of transparent recycling chains stems from specific application requirements. Brands may adopt transparency to justify their use of recycled materials or combat fraud in the recycling process. Although BCT advocates decentralised governance, the degree of data visualisation of stakeholders may be different (Ziolkowski, Miscione, and Schwabe 2020). For example, traceable recycling flows are effective for municipal departments to supervise, whereas recycling companies are unwilling to share their data with competitors. Going further, it is expected to achieve an ideal state as the BCT adoption can improve fair benefits distribution among recycling chain members.

For service transformation, evaluating performance indicators should target dynamic considerations since objectives may vary in different stages (Kshetri 2018). In the early stage, focal companies may tend to rely on networking benefits due to the high investment cost, which they expect others to share. In further scale-up, dependability, risk, and cost may become more important. A reliable credit system and operations cost savings can maintain the stability of operations, which can generate competitive advantages for expansion and even form economies of scale (Liu, Zhang, and Medda

2021). In the maturation stage, the triple bottom line effects link with brand image promotion. For those companies that pursue environmental and social effects, engaging informal sector participation can form larger scales of waste collection. Also, they can demonstrate CSR and, ultimately, scale-up operations by cooperating with influential stakeholders such as multinational companies and municipal departments (Gong et al. 2021). Therefore,

Proposition 3: *BCT can ideally enhance recycling chain performance when initiators have reasonable application requirements and the application benefits of stakeholders are fairly distributed, while targeted recycling chain objectives may vary in different application stages.*

Focal companies should consider application feasibility in a more realistic exposition. The crucial point is the BCT type, which determines business functions (Saberi et al. 2019). The anonymity and decentralisation features encouraged by most research are derived from the permissionless (public) type (Ziolkowski, Miscione, and Schwabe 2020). Conversely, for those who wish to have tighter recycling chain control, the permissioned (private) version would be more suitable. However, the permissioned type can be regarded as a special way of running the shared database by supporting cybersecurity while some BCT functions may be degraded.

Furthermore, the BCT version shapes the design of decentralised networks, which impacts the overall performance. Although BCT is seen as a disruptive tool to form collaboration and integration(Lumineau, Wang, and Schilke 2021), it is important to design incentives for participation given entry boundaries (who can join), enhance role accountability and effective information sharing among members (Beck, Müller-Bloch, and King 2018). These considerations make up the concept of blockchain governance, including the algorithm and protocol design at the on-chain layer and wider community and software development at the off-chain layer decisions (Ziolkowski, Miscione, and Schwabe 2020).

To design a robust decentralised network structure, members should first set explicit participation mechanisms, i.e., the membership of who can join. Subsequently, the definition of roles at different levels needs to be defined in full to ensure that members can fulfil the appropriate division of responsibilities (Wang, Chen, and Zghari-Sales 2021). This also leads to incentive mechanisms including the intrinsic motivation of members to contribute to the community (Beck, Müller-Bloch, and King 2018). The way in which members communicate constitutes the guideline for coordinated actions, the core of which lies in standardisation, e.g., data feeding and reading approaches are standardised in the tracking system. To align the implementation of the network, it is crucial to define the distribution rights of decision-making, for example, what consensus mechanisms are applied to shape and monitor decisions (Ziolkowski, Miscione, and Schwabe 2020). It can be led by traditional boards and general assemblies, or it can be achieved through a network autonomy organisation set up by the members to balance central leadership and shared control (Wang, Chen, and Zghari-Sales 2021).

In the recycling scenario, the ideal network governance structure is inclusive and open to all recycling practitioners. Operational guidelines are mutually established and recognised by members. A more practical consideration would be to design the coordinator role within the network, responsible for coordinating and controlling network activities, and the validator role, who can assist in monitoring the authenticity of data input (Danese, Mocellin, and Romano 2021). Therefore, the construction of such networks requires the development of reasonable boundary settings equipped with tailored incentive mechanisms. In other words, in addition to setting clear thresholds for membership, it is important to design mechanisms that provide incentives for members to spontaneously join and contribute to the community. Ideally, members would reap the benefits of joining the network voluntarily rather than through compulsory enforcement, e.g., participants receiving recycling rewards, brands demonstrating transparent accountability, and suppliers gaining extra orders as identified in Section 5.1.3.

From the immutability of the technical aspect, some BCT proponents applauded the fact that it could bring radical changes to data storage and transaction, such as its broad use in anti-counterfeiting measures (Danese, Mocellin, and Romano 2021). However, immutability only works when the data are trustable in the first place to avoid 'garbage in garbage out' issues (Ziolkowski, Miscione, and Schwabe 2020). Moreover, data accessibility right in actual applications has been largely overlooked. In the BCT recycling network, the division of data feeding, and reading is essential to guarantee recycling chain coordination (Danese, Mocellin, and Romano 2021). Specifically, it should be equipped with a reasonable design without infringing privacy issues and intellectual property (Chen and Ogunseitan 2021). Furthermore, the extent to which smart contracts can improve existing information systems (e.g., efficiency and speed) needs to be further confirmed. These technical considerations lead to a further debate – i.e., what are the real benefits of the BCT system over traditional information systems (Ongena et al. 2018).

The identification of waste categories is also crucial. Different waste types have corresponding recycling processes, leading to the standardisation issue (Taylor, Steenmans, and Steenmans 2020). For example, kitchen waste cannot achieve as high a degree of transparency as recyclables can. There are complexities in handling compound recyclables (e.g., disassembly of recyclables and separating them into different parts). Also, BCT works as a database storage system, recording the inputs and outputs during recycling processes. However, it cannot interpret what happens inside the 'Blackbox'. In other words, the limitation appears at the nexus between physical things and digital identity (Choi 2019). For example, some manufacturers claim that they use recycled plastic, but intermediate processing (e.g., adding virgin plastic) is difficult to monitor. This ethical issue calls for external audit bodies to supplement verification.

Furthermore, the high cost of practical implementation cannot be overlooked. Consider an example of verifying products that claim to be made from recycled plastic. In BCT applications, batch scanning is a common way to complete digital recordings (Wang, Han, and Beynon-Davies 2019). However, when marginal costs of digital records of recycled materials (guarantee that materials load conform to specified specifications and securely labelling each batch) are higher than their expected outcomes (prove the authenticity of recycled materials), feasibility performance will be negligible due to the high costs involved. In other words, practical cost affects BCT functionality. Therefore,

Proposition 4: *The BCT application faces practical limitations in terms of technological and application scenario perspectives, which may mitigate potential performance.*

7. Conclusion and implications

This study explores current state-of-the-art BCT applications in recycling chains via a content-based review method. Through thematic analysis, this study showed that BCT has transparent, integration, behaviour channelisation, and service transformation functions. However, technical, organisational, and environmental limitations remain to be overcome and may affect adoption behaviour and further scale-up. Also, the BCT application can enhance the recycling performances of cost, dependability, flexibility, sustainability, and risk reduction. It can be concluded that it is unrealistic to rely solely on BCT to solve the global waste management crisis as BCT will not be a panacea. BCT can be used as an auxiliary tool when supportive conditions are in place – i.e., it can be useful as an element in the socio-economic system (Saberi et al. 2019).

7.1 Theoretical implications

This research makes the following theoretical contributions. Emerging studies identified how BCT can contribute to SCM in terms of traceability and trust (Dubey et al. 2020; Hastig and Sodhi 2020; Pournader et al. 2020). however, there was less exploration of BCT application in recycling chains to tackle the waste management crisis (Saberi et al. 2019). This study particularly enriches the research on BCT in SSCM, with a specific focus on the recycling chain through a rigorous content-based review. It serves as an extension of BCT in SSCM and responds to the research call from Erhun, Kraft, and Wijnsma (2021), which promotes the study of technical, social and environmental dimensions for sustainable triple-A (agile, adaptable, and aligned) supply chain. Also, the proposed '*Stimulus, Response and Performance*' conceptual framework helps us to understand the logic chain of the BCT adoption for sustainable practices (Reuter et al. 2010), thereby enriching the theoretical construction of BCT-driven sustainability.

This paper also theoretically integrates determinants of BCT adoption through the TOE framework and summarises potential performance from recycling chain objectives and practical feasibility limitations. In general, BCT empowers innovative solutions for SSCM, and our research enriches relevant studies from the recycling chain perspective. Our research thereby offers valuable insights to SCM researchers, laying a foundation to motivate more explorations in BCT and sustainability, such as the emerging topics of carbon neutrality and climate change (Saberi et al. 2019).

7.2 Practical implications

From the managerial perspective, this study has significant relevance to practice. It provides a comprehensive review of the functions of BCT in recycling, which can inform those practitioners seeking suitable waste management solutions. Additionally, the practical limitations and potential performance of the BCT application can effectively support focal companies in weighing the pros and cons of BCT adoption. Also, for focal companies looking to embrace the circular economy, this study provides innovative BCT solutions driven by 'Industry 4.0' trend that assist focal companies in their digital transformation and sustainable advancement. In general, this study offers valuable insights for both scholars and practitioners to tackle the recycling crisis, optimise waste management, and achieve higher sustainability performance among recycling chains.

However, some limitations should also be noted. Considering the early research stage of BCT application, only a limited number of papers were identified for thematic analysis, and other functions and feasibility limitations may exist in practice. In order to obtain a more comprehensive review, we have not narrowed our review down to specific waste types and regional contexts. Rather, it was specific to the recycling chain context, which may constrain the generalisation to other sectors. Also, the proposed application framework was integrated from conceptualisation, which calls for more empirical evidence to further verify it.

7.3 Future research direction

We identified various promising and novel topics that have been under-explored to promote BCT studies. Future studies can build upon our findings to enrich further studies.

Theory-based empirical research

Existing studies are mainly based on conceptual discussions and more in-depth empirical research is needed (Hastig and Sodhi 2020). Empirical studies can generate emerging discoveries and supplement the proposed conceptual framework. It is also interesting to explore under what conditions the BCT practice can be successful and why some BCT practices have failed or stalled (Wang, Han, and Beynon-Davies 2019). Strong empirical research needs theoretical guidance. For instance, the *resource-based theoretical view* can explain how BCT improves supply chain performance as a competitive advantage (Karakas, Acar, and Kucukaltan 2021); *network theory* can promote inter-organisational performance through supply chain network cooperation (Gong, Xie, et al. 2022); the *transactional cost view* can explore how to build an effective governance mechanism in terms of bounded rationality and opportunism (Roeck, Sternberg, and Hofmann 2020); and the *technology acceptance and innovation adoption theory* can help to indicate the BCT implementation stage (Queiroz et al. 2021). Nevertheless, more theories need to be explored and the proposed middle-range theory should be applicable to real-world practices (Wang, Chen, and Zghari-Sales 2021).

Decision-making behaviour of BCT initiators

Actual applications of BCT are initiated in specific conditions and for different purposes. BCT initiators may seek business model transformation, echo regulatory requirements, and even respond to consumers' demands for transparency. Exploring the early application behaviour of BCT can help practitioners to understand the motivation of BCT initiators and support other potential adopters to make decision analyses (Saberi et al. 2019).

Blockchain technology governance

The BCT application may reconstruct existing recycling chains, raising the question of how to generate and maintain the BCT-based recycling chain governance. Traditionally, contractual and relational governance are essential tools to align interests among stakeholders. BCT may provide a new way to enforce coordination and collaboration (Lumineau, Wang, and Schilke 2021). From most application cases, it can be found that a purely decentralised governance mechanism may not always be applicable (Wang, Chen, and Zghari-Sales 2021). Relevant and timely questions arise from this discussion; for example: Who designs the BCT system rules? What are the boundaries to joining the BCT system? What are the incentives that can be employed to attract more members to join? How can the behaviour of members be coordinated and monitored? How can a consensus mechanism be generated through decision-making? How do the governance mechanisms derived from blockchain fit into the existing organisational structure and what are the dynamic benefits? These important questions deserve further consideration.

Investigating immutability issues

The transparent recycling chain is realised through immutability, based on the requirement that the data are trustable and reliable. Data fraud and error often occur between the conversion of physical entities and digital identities, so it is crucial to ensure that the input data are trustable and authentic in the BCT system (Choi 2019), which may be supplemented by other technologies or other protocol mechanisms. Existing proof of tamper-evident properties usually requires assistance, e.g., certification bodies and endorsement by the brand owner. The role of these supplementary approaches to aid verification and the combination with BCT needs future exploration.

Long-term performance evaluation

Expensive upfront investment costs and unknown risks have discouraged potential pioneers. For most practitioners, it is imperative to consider to what extent BCT can improve the existing recycling chain or what benefits can be obtained, and the implications for BCT initiators. It may need to be compared with other information systems – i.e., what benefits BCT can bring those other technologies cannot. In addition, the benefits should not be simply measured from economic perspectives, but social and environmental aspects should also be considered.

Localisation application

Waste management involves diverse background situations, such as different recycling patterns in developing countries and developed countries (Gong, Xie, et al. 2022). These localisation and operational differences may affect the choice of BCT versions. Also, different waste types have no uniform standardisation. Based on different application scenarios and background factors, the specific and comparison studies of BCT applications need to be further expanded.

Multiple disciplines lens

Finally, BCT application in recycling chains calls for research from multiple disciplines such as social science (e.g., consumer behaviour, public policy, business model, recycling economics, operation research); environmental management and engineering (e.g., life cycle analysis, waste material flow); and information systems and management (e.g., BCT protocol, system, and function design). Thus, we call for more multi-discipline and cross-discipline collaborations and research on this promising and important topic.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Appendix 1 Summary of selected papers

No.	Authors	No.	Authors
1	Saberi, Kouhizadeh, and Sarkis (2018)	24	Steenmans *et al*. (2021)
2	Gopalakrishnan and Ramaguru (2019)	25	Voorter and Koolen (2021)
3	Morrow and Zarrebini (2019)	26	Bamakan *et al*. (2022)
4	Saberi et al. (2019)	27	Alves *et al*. (2022)
5	Zhang (2019).	28	Chaudhuri *et al*. (2022)
6	Chidepatil et al. (2020)	29	Gong, Wang, et al. (2022)
7	Esmaeilian et al. (2020)	30	Gong, Xie, et al. (2022)
8	França et al. (2020)	31	Hrouga, Sbihi, and Chavallard (2022)
9	Hakak et al. (2020)	32	Júnior et al. (2022)
10	Howson (2020)	33	Samadhiya et al. (2022)
11	Liu et al. (2020)	34	Song et al. (2022)
12	Taylor, Steenmans, and Steenmans (2020)	35	Wang, Ma, and Hu (2022)
13	Ahmad, Salah, Jayaraman, Yaqoob, and Omar (2021)	36	Ongena et al. (2018)
14	Ahmad, Salah, Jayaraman, Yaqoob, Omar, et al. (2021)	37	Schmelz et al. (2019)
15	Ajwani-Ramchandani et al. (2021)	38	Akbarieh et al. (2020)
16	Centobelli et al. (2022)	39	Sahoo and Halder (2020)
17	Chaudhary et al. (2021)	40	Kassou et al. (2021)
18	Chen and Ogunseitan (2021)	41	Climate (2020)
19	Damadi and Namjoo (2021)	42	Katz (2019)
20	Gopalakrishnan, Hall, and Behdad (2021)	43	Lenz (2021)
21	Khadke et al. (2021)	44	Peshkam (2019)
22	Liu, Zhang, and Medda (2021)	45	Gong et al. (2021)
23	Sahoo, Mukherjee, and Halder (2021)		

Note: Nos. 1-35 are journal articles, Nos. 36-40 are conference papers, Nos. 41-44 are reports, and No. 45 is a teaching case.

Table 1 Characteristics of blockchain technology

Characteristics	Explanation
Decentralised/ disintermediation	Transaction data on the system are not verified by a central controller or through a third party
Transparent /Visibility	All input data will be saved, and the consensus mechanism guarantees that any data modification will be recorded
Anonymity	Distributed ledger connects multiple nodes, but the identities are anonymous
Immutable/ Irreversible	Blockchain guarantees immutability through timestamp and permission control restrictions, and each transaction and data can be verified
Smart contract	Smart contract promotes the convenience of transaction response while having higher security and lower transaction costs

Sources: Adapted from: Wang, Han, and Beynon-Davies (2019); Dolgui et al. (2020); Koh, Dolgui, and Sarkis (2020) and Pournader et al. (2020)

Table 2 Review methodology protocol

Database	Scopus, Web of Science, EBSCO
Search strings	('blockchain' OR 'distributed ledger' OR 'smart contract') AND ('recyc*' OR 'waste management' OR 'municipal waste' OR 'solid waste' OR 'plastic')
Initial broad inclusion	
Search fields	• Titles, abstracts and keywords
Publication type	• Journal articles, conference papers
Language	• English
Data range	• Updated to June 2022
Context	• Whether papers fell within the context of blockchain technology and recycling
Inclusion criteria	• Papers focus on BCT in recycling/waste management sector

	• Papers involve at least one of the aspects of the BCT application in recycling chains (functions, application limitations and performance) • Papers focus on the management aspect or describe business models of BCT application in recycling chains • Document type: journal articles, conference papers
Exclusion criteria	• Focus on other technology applications (e.g., internet of things, artificial intelligence) in recycling/waste management without mentioning BCT • Focus on BCT applications in other sectors • Focus on BCT applications in general sustainability or the circular economy (not specifically to recycling) • Focus on technical aspects of BCT (e.g., BCT architectures, smart contract design, fintech, etc) • Document type: other types
Unit of analysis	• Selected articles

Table 3 Blockchain technology functions in recycling chain

Theme	Sub-themes	Supporting references
Transparency	Waste data/ information integrity	2,4,5,6,7,8,9,10,11,12,13,14, 15,17,18,19,20,21,22,23,24, 27,28,29,30,31,32,34,35,39
	Waste traceability	2,3,4,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,27,28,39,30,31,32,34,35,38,39,40
	Waste accountability	2,4,5,8,9,10,11,12,13,17,18, 19,20,21,22,25, 27,28,39,30,31,32,34,35,38
Integration	Multi-party coordination	4,6,7,8,10,16,17,18,19,20, 21,22,25,29,30,32,35,36,37, 38

	Social inclusion	8,9,10,20,25,26,35,36,37,39,41,42,43,44, 45
Behaviour channelisation	Recycling rewarding	2,3,4,6,8,9,10,14,18,20,25,28,29,3033,35,36,37,38,39
	Recycling supervision	3,8,9,10,16,18,20,25,27,28,29,30,33,35,37,38,39,41,42
Service transformation	Strategic consideration	8,10,15,19,21,36,37,38,39,45
	Recycling process optimisation	3,5,7,9,12,13,18,19,21,22,25,26,27, 28,29,30,32,35,36,37,38,39

Table 4 Blockchain technology feasibility limitations in recycling chain

Theme	Sub-themes	Supporting references
Technical dimension	Immutability/recording adverseness	1,4,14,18,29,30,31,35,36,39,41,42,43,45
	Privacy issue	1,4,14,18,30,31,39,45
	Inherent design flaws	4,14,18,30,31,39,42,45
	Immature blockchain technology	1,2,3,4,8,14,18,21,23,24,25,29,30,31,39,41,42
Organisational dimension	Organisational readiness	4,18,30, 39,45
	Stakeholder acceptance	1,4,14,16,30,39,45
	Stakeholder commitment	4,8,14,16, 30, 39,45

Environmental dimension	Recycling chain compatibility (internal)	1,4,8,14,18,30,31,32,39,42,43,45
	Industry constraint (external)	1,4,8,14,18,30,31,39,44,45

Table 5 Recycling chain performance by blockchain technology application

Recycling chain objectives	Content	Explanation	Supporting reference
Cost-saving	Supervision cost	Disintermediation reduces traditional third parties' waste management supervision costs	3,4,9,10,18,26,28,36,39
	Operational cost	Combined with other technologies, achieving operational savings, such as waste collection, sorting optimisation, efficient waste transportation	4,7,13,18,26,2839
Dependability	Constraint behaviour	Recycling chain members are required to perform proper recycling based on smart contracts	4,6,8,9,18,20,25,33,39,40.41
	Reliable system	Trust free identity authentication and immutable mechanism to maintain data integrity	3,4,5,9,10,12,14,17,18,19,20,22,23,31,39,39

Flexibility	Networking effect	Networking effects promote multi-party coordination, which can enhance resource integration and information sharing	2,4,6,8,17,18,20,27,30,32,35,38,39
	Speeding process	BCT can automatically track, and record recycling processes while the digitalised recycling chain can simplify procedures and improve collection, separation, and transportation efficiency	3,5,7,9,12,16,18,20,21,23,24,25,27,29,31,35,36,39
Sustainability	Environmental	Improve municipal waste management and protect the ecological environment (e.g., prevent waste from flowing into landfills or oceans)	4,6,8,11,13,18,20,35,38,39,42,43,44,45
	Social	Achieve SDGs by engaging informal sectors, forming recycling behaviour, and improving employment and social welfare	4,6,8,10,11,18,20,35,36,37,38,39,41,42,43
	Economical	Higher resource utilisation, innovative business model, kindle entrepreneurship	4,6,8,11,18,20,28,30,35,36,37,38,39

Risk reduction	Tackle information asymmetry (fraud)	Prevent fraud and enhance the security of waste management information systems	3,7,8,9,10,12, 13,14, 15,17, 18,20, 21,22, 23,24, 30,31, 32,34, 35,38, 39
	Fair recycling business	Maintain fair waste trade by enhancing information sharing and reducing cash transactions; tackle smuggling trade and illegal cross-border dumping	10,18, 31,41, 42,43, 44,45

Source: Adapted from: Kshetri (2018)

Figure 1 Milestones in the conducting of content-based literature reviews

Figure 1 Alt text: This research follows four stages in conducting the content-based literature review including material collection, descriptive analysis, analytics categories and material evaluation, and research quality.

Stage 1 Material collection				
Defining and delimitating material	Specifying topic with search strings	Selecting database	Defining unit of analysis	Consistent throughout the analysis

⇩

Stage 2 Descriptive analysis	
Distribution over time period	Distribution over publication outlets

⇩

Stage 3 Analytic categories	
Deductive category building	Iterative cycles of inductive category refinement with coding

⇩

Stage 4 Material evaluation and research quality			
Iterative coding cycles	Transparent and objectivity	Reliability	Validity

Source: Adapted from Seuring and Gold (2012)

Figure 2 Screening process

Figure 2 Alt text: This figure shows the detailed steps of the screening process. The review includes both academic sources from Web of Science, Scopus and EBSCO databases and grey literature. After the detailed screen process, the final selection sample size is 45.

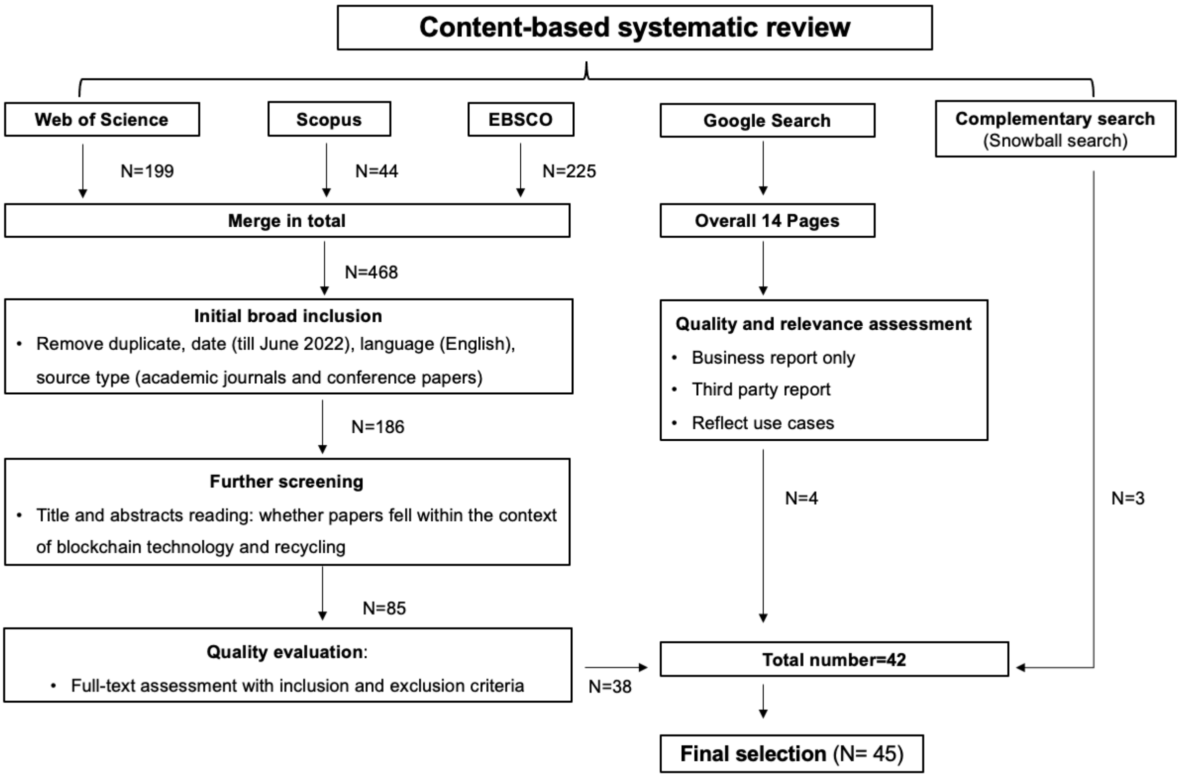


Figure 3 Papers published up to June 2022

Figure 3 Alt text: This figure presents the distribution of the published papers per year from 2015 to June 2022. The distribution shows a rapid increase of the selected papers.

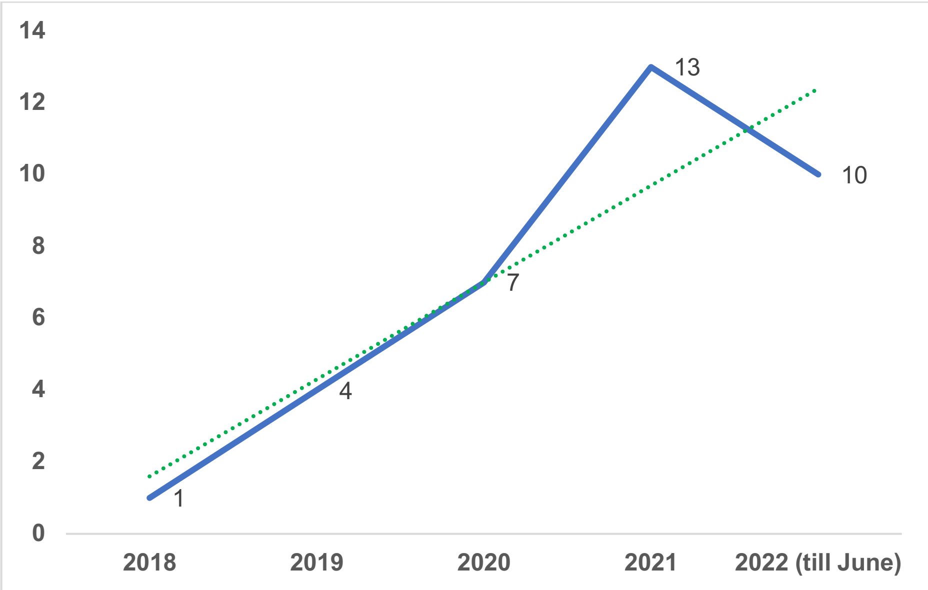


Figure 4 Distributions of journals

Figure 4 Alt text: This figure presents the distribution of selected journal papers. Therein, 34% of the selected journals are from the ABS Journal List and those from other lists account for 66%.

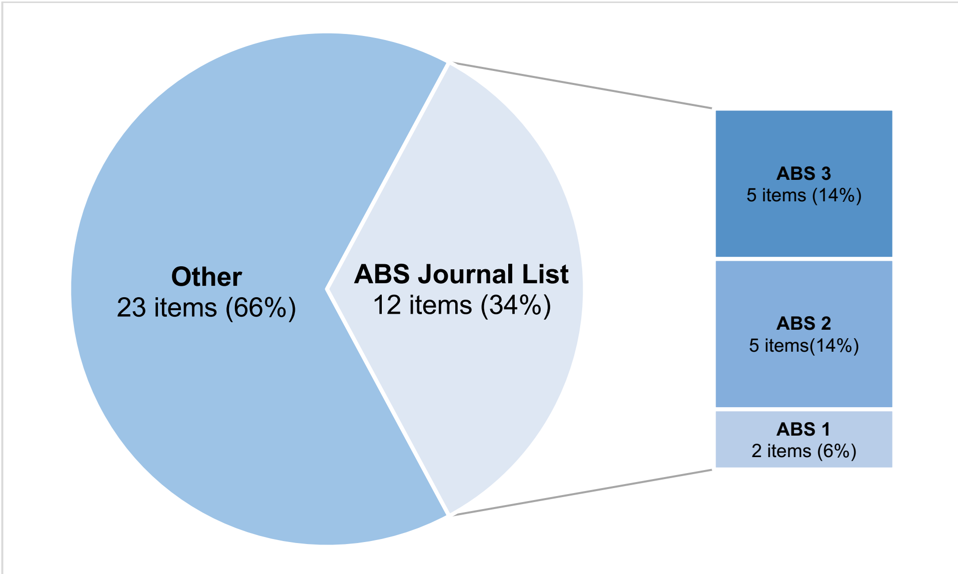


Figure 5 Research methods applied to selected journal papers

Figure 5 Alt text: This figure presents the research methods applied to selected journal articles. The most commonly used research type among the selected items is conceptual, with 15 items, followed by case study and review, both with eight items, and the modelling approach used by four items.

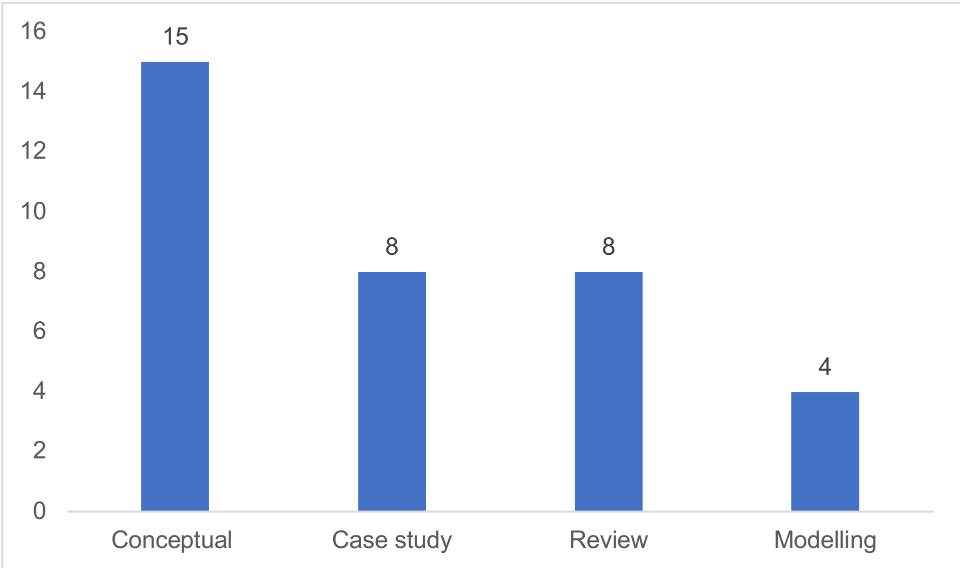
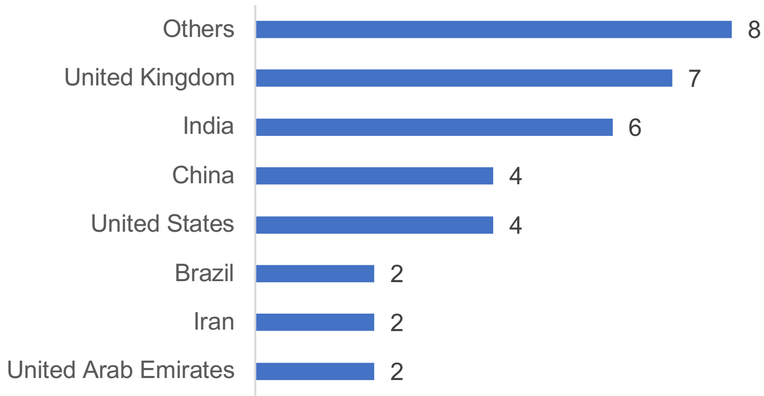


Figure 6 Geographical distribution of selected journal papers

Figure 6 Alt text: This figure presents the regional distribution of selected papers. It is led by the UK and India with seven and six articles respectively, followed by China and the USA with four articles each, and Brazil, Iran and the United Arab Emirates with two articles each. Some of the regions that appear only once have a total of eight articles.



Note: The ‘Others’ category refers to the region that only appears once

Figure 7 Waste type focus of selected journal papers

Figure 7 Alt text: The reviewed journal papers focus on a wide range of waste types including general waste, plastic waste, municipal solid waste, electronic waste and others following a descending sequence.

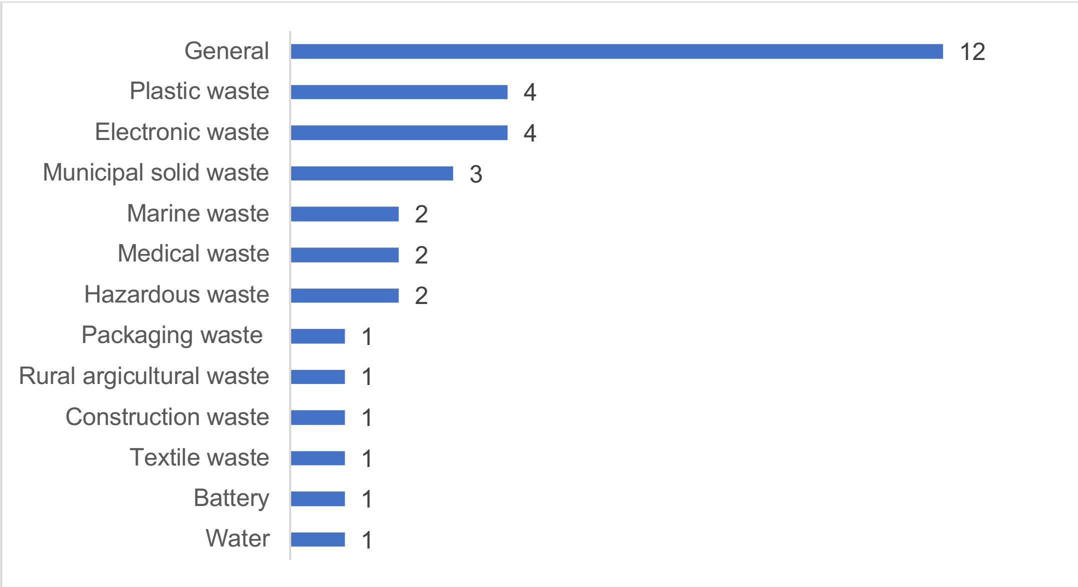


Figure 8 BCT functions in the recycling chain

Figure 8 Alt text: BCT functions in the recycling chain can be summarised into four categories with subfactors including transparency (waste data/information integrity, waste traceability, waste accountability), integration (multi-party coordination, social inclusion), behaviour channelisation (recycling rewarding, recycling supervision), and service transformation (strategic consideration and recycling process optimisation).

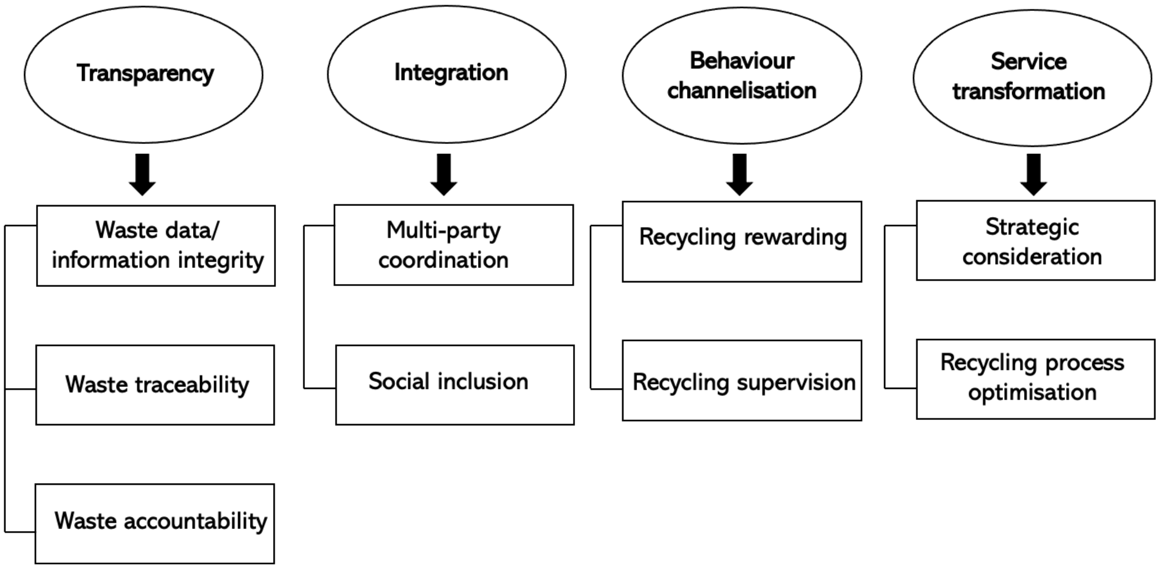


Figure 9 BCT feasibility limitations in the recycling chain

Figure 9 Alt text: The adoption of BCT in the recycling chain faces three obstacles; these are technical aspects (immutability/recording adverseness, privacy issue, inherent design flaws, immature blockchain technology), organisational aspects (organisational readiness, stakeholder acceptance, stakeholder commitment), and environmental aspects (internal recycling chain capability, external industry constraints).

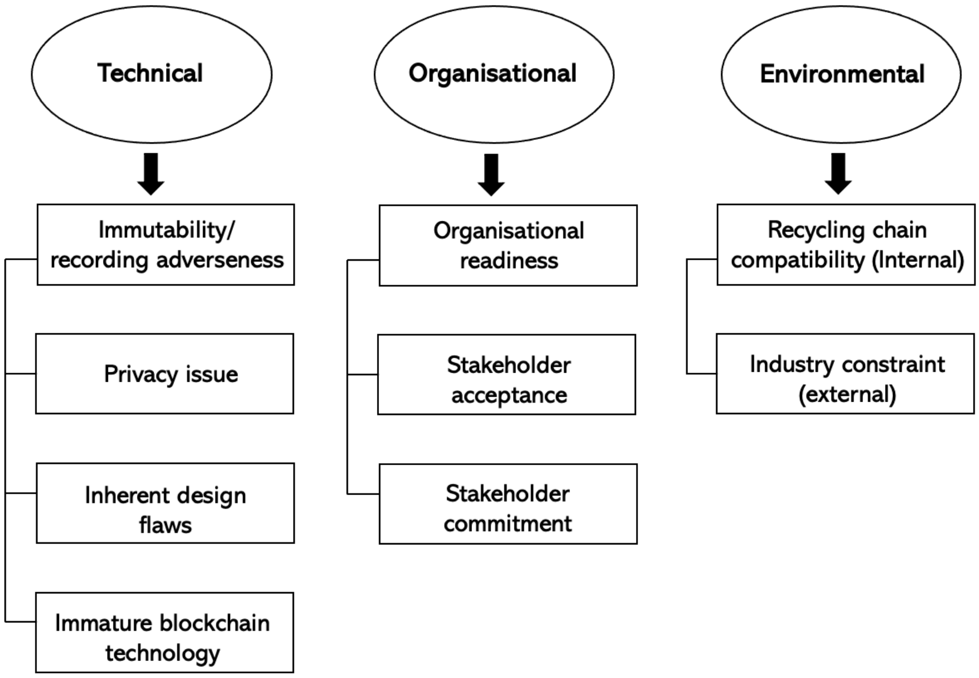


Figure 10 Conceptual framework of BCT application in recycling chain

Figure 10 Alt text: This figure presents the conceptual framework of BCT application in the recycling chain. BCT adoption is driven by stimulus factors such as waste management chaos and digitalisation trend/BCT relevance potential, which could lead to the response of BCT application (proposition 1). The application process is influenced by technical, organisational, and environmental factors (P2a, P2b, P2c propositions). The application could further lead to performance improvement in terms of meeting recycling chain performance objectives (proposition P3) and performance uncertainty in terms of potential application challenges (proposition P4).