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Blockchain-based recycling and its impact on recycling performance: A network theory perspective

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Abstract

The purpose of this study is to explore the application of blockchain technology (BCT) in recycling. This research applies a multiple case study approach with six pioneer organisations, based on secondary data. We found that BCT is an effective approach to promote recycling performance: it can provide tokenisation, waste flow tracking and recycling chain integration. The benefits include 'Eco-friendly', 'Stimulate participation', 'Social inclusion', 'Transparent recycling chains' and 'Extended producer responsibility accountability'. However, the majority of existing BCT-based initiatives are in the pilot stage and face cognitive, technology, internal and external barriers. Our research is one of the first studies on blockchain-based recycling. We applied the network theory of 'Reachability', 'Richness' and 'Receptivity' and 'network formation' barriers to propose a conceptual framework of BCT-based recycling, which serves as a practical reference for the recycling industry.

KEYWORDS

blockchain technology, circular economy, network theory, recycling chain, sustainability, sustainable supply chain

1 | INTRODUCTION

The rise of Industry 4.0 is driving transformations of business models, including revolutionising traditional businesses, and forming competitive organisational networks (Bai et al., 2020). The advanced technologies of Industry 4.0 such as Big Data, Artificial Intelligence (AI) and Internet of Things (IoT) not only can promote productivity (Awan et al., 2021) but also open up the possibilities of realising circular economy (CE) and sustainable supply chains (SCs) (Bai & Sarkis, 2020; Kumar et al., 2021; Massaro et al., 2021).

Blockchain technology (BCT) as one driving technology of 'Industry 4.0' has been increasingly explored by academic and industrial fields. In academia, the concept of BCT in improving SC performance is increasingly deepened (Kshetri, 2018). Babich and Hilary (2019) concluded the advantages and disadvantages of BCT in operations management; and BCT can improve the visibility and traceability of SC (Hastig & Sodhi, 2020; Rogerson & Parry, 2020). Empirical studies of BCT to industries such as agriculture, fishery, luxury goods and E-commerce based on visibility and traceability of BCT have investigated these in detail (Kouhizadeh et al., 2021; Kshetri, 2018). Furthermore, industrial fields see BCT as a critical part of organisational innovation. The survey of Deloitte (2020) showed that BCT represents the real driving force for radical revolutions, with 88% of respondents believing that BCT is widely extensible and will eventually be the mainstream.

BCT also shows excellent potentials in CE reformation. Sarkis and Zhu (2018) showed that sustainability in production and operations management will ultimately yield healthy returns to society, while BCT can be an excellent driver. Saberi et al. (2018) proposed a conceptual framework to show that BCT can contribute to sustainable SCs. Kouhizadeh et al. (2019) extended empirical studies of BCT on CE by different industries and confirmed the long-term impact of BCT on economic, social and environmental aspects.

Abbreviations: EPR, extended producer responsibility; BCT, blockchain technology; SCM, supply chain management; CE, circular economy; SC, supply chain; B2B, business-to-business; B2C, business-to-customer.

Recycling is an essential component of CE, but traditional recycling chains are mainly linear with unresolved challenges. The appalling volume of waste generation is predicted to increase to 3.5 billion tonnes by 2050, while the disposal by recycling is only 13% of this volume (The World Bank, 2018). Behind these alarming figures lies the evasion of responsibility by recycling chain members. However, the current opaque recycling chain process has led to waste-tracking difficulties. The traceability issues are even more chaotic after a waste ban by China, which used to be the biggest waste import country, followed by more countries that enacted strict waste import (Wen et al., 2021). As a result, the volumes of waste flows are unknown, although we do know that much of this ends up in the oceans. Evasion of responsibility also breeds illegal waste trade, such as transporting to and dumping waste in other countries. This has generated lucrative businesses which operate outside of regulatory systems. Also, for developing countries, most waste management activities are led by informal recycling sectors, such as street pickers, who are paid very little and have to work in conditions of poor sanitation, and with unrecognised identities (Agrawal & Singh, 2019). The weak recycling awareness and fragmented cooperation between recycling chains exacerbate the chaos of waste management. Therefore, it is imperative to introduce a tracking system to trace waste flows and form an incentive mechanism to integrate recycling chain members; this is an area where BCT could be a potential solution.

BCT shows great potentials in tackling these recycling challenges. In practice, some pioneer organisations have kicked off the BCT project to tackle recycling issues (França et al., 2020; Hande, 2019; Katz, 2019). For example, *Plastic Bank* and *IBM* developed a BCT-based platform in developing countries to tackle the plastic waste crisis by offering tokens. This innovative recycling model not only shows outstanding recycling efficiency but also offers exceptional contributions at the social level. Also, the start-up *Circularise* built a BCT-based data platform to ensure transparent data-sharing between suppliers, manufacturers and recyclers, where sustainable recycled plastics can be certified and marketed (Peshkam, 2019).

The rise of these innovative recycling models suggests that such practices are leading the field, with academic research following the trend. Saberi et al. (2019) proposed that BCT can offer cryptographic tokens to motivate residents and provide tracking data for waste lifecycles. Esmaeilian et al. (2020) conceptualised that BCT can promote green behaviour, enhance lifecycle visibility and improve sustainability reporting. In practice, França et al. (2020) illustrated how BCT can be applied in waste management in Brazilian municipalities, while Chidepatil et al. (2020) explored the combination of BCT and AI to improve plastic waste recycling. Howson (2020) depicted the potentials of BCT to reduce pollution from plastics in marine conservations. However, most existing studies focused on the conceptual building of BCT potentials for recycling. They described possible solutions based on characteristics of BCT but lacked exploration of practical solutions. Specifically, empirical research on how to embrace BCT in actual waste management situations is missing. Also, it is necessary to systematically explore the benefits and barriers of using BCT since it cannot be a panacea. Thus, this research aims to fill this gap by answering the following questions:

1. How can BCT be used to improve recycling performance?
2. What benefits can the application of BCT bring to recycling?
3. What are the barriers to adopting BCT in recycling?

In order to answer the above questions, a case study based on secondary data of six BCT-based recycling practices is applied. Recycling performance requires multi-party participation while BCT provides an innovative means to integrate original fragmented networks. It is imperative to explore how such embeddedness of inter-organisational ties jointly contribute to recycling performance. Hence, we applied the inter-organisational network perspective from Gulati et al. (2011) to explore the mechanism that drives performance effects. Three multifaceted ways of 'Reach', 'Richness' and 'Receptivity' are applied to elucidate how recycling chain members access, integrate and leverage network resources. Also, the 'network formation' considerations are applied to explore the BCT implementation barriers (Birkinshaw et al., 2007).

The significance of this study lies in that the case companies provide innovative solutions for recycling and further deepen the impetus of technology-driven sustainable development. We conclude that BCT can provide fruitful functions to tackle recycling issues although it still faces uncertainties. This research is one of the first empirical studies on 'blockchain and recycling' by exploring worldwide pioneering recycling companies. It contributes to in-depth empirical research of BCT in CE and specifically in recycling. It also contributes to the 'Network Theory' by adding network formation and highlights the network effects in BCT-based recycling chains. Also, it enriches the understanding of emerging technologies to achieve sustainability under 'Industry 4.0' promotions with innovative waste management solutions.

The remainder of the paper is structured as follows: Section 2 reviews current research on BCT and applications in SC, BCT and recycling chain, and network theory. Section 3 presents the detailed research methodology. Section 4 carries out the cross-case analysis on BCT recycling solutions, benefits and implementation barriers. Section 5 provides further discussions based on cross-case analysis by applying network theory, which leads to a conceptual framework and proposition development. Finally, Section 6 concludes with the main findings, theoretical and managerial contributions, limitations and future research directions.

2 | LITERATURE REVIEW

2.1 | BCT and supply chain management (SCM)

BCT triggered a new round of technological innovation exploration and industrial transformation (Hastig & Sodhi, 2020; Saberi et al., 2019). BCT started in the financial sector, where the underlying technology of Bitcoin was popularised (Nakamoto, 2008). The technology was subsequently expanded to other industrial applications with traceability and immutability features (Dutta et al., 2020; Wang et al., 2019). Also, BCT shows great potentials for improving sustainability and the CE with the rise of 'Industry 4.0' concepts (Kumar et al., 2021; Saberi et al., 2019).

In essence, BCT is a decentralised database that does not rely on third parties and uses distributed nodes for data storage, validation and delivery (Queiroz et al., 2019). The characteristics include 'decentralisation', 'openness', 'independence', 'security' and 'anonymity' (Dutta et al., 2020; Hastig & Sodhi, 2020). Decentralisation is the most prominent feature, which implies that each node can realise information self-verification, transmission and management without additional third-party control (Wang et al., 2019). Openness refers to the highly transparent feature, allowing parties in public chains to query blockchain data (Cole et al., 2019). A high degree of *independence* in BCT can be achieved by agreed-upon specifications and protocols, named 'Smart Contract', which can automatically verify and enforce when contract terms are met (Kouhizadeh et al., 2019). The high *security* means it can effectively avoid artificial tampering, and the identity information of each block node is *anonymous* rather than exposed to general scrutiny (Danese et al., 2021; Tönnissen & Teuteberg, 2020).

The rise of BCT is particularly evident in SCs (Cole et al., 2019; Dutta et al., 2020; Hastig & Sodhi, 2020). Most articles reviewed the benefits of BCT for SCM conceptually. Babich and Hilary (2019) concluded the key strengths, including visibility, aggregation and validation, automation and resiliency. Hastig and Sodhi (2020) systematically summarised business requirements and critical success factors of BCT application for achieving SC traceability by reviewing 75 papers. It demonstrated that BCT could integrate various stakeholders' and companies' capabilities which are essential for attaining traceability performance. Particularly in the food industry, it can transparently show SC processes and track product footprint, with great potentials to increase consumer confidence. Also, it can prevent fraud in food SCs with the promotion of visual digitalisation (Hastig & Sodhi, 2020; Mukherjee et al., 2021; Rogerson & Parry, 2020).

Kshetri (2018) conducted 11 case studies to prove that BCT can achieve better strategic SC objectives, including cost-saving, speed, dependability, risk, sustainability and flexibility. The disintermediation feature can reduce hierarchical transactions and save time (Tönnissen & Teuteberg, 2020). Moreover, the implementation of BCT can speed up data flow, which helps improve efficiency and reduce costs in logistics and SCM (Pournader et al., 2020; Wang et al., 2019). Martinez et al. (2019) found that BCT can improve customer order efficiency, including order efficiency improvement, order traceability and data sharing among SC stakeholders. Furthermore, a high degree of security and authenticity can provide more reliable business and effectively prevent data manipulation (Danese et al., 2021; van Hoek, 2019).

However, applications of BCT in SCM are still in the pilot stage, with many related uncertainties and barriers. Babich and Hilary (2019) came up with general weaknesses such as lack of privacy, lack of standardisation, 'black box effect' and inefficiency. van Hoek (2019) summarised the main implementation barriers to BCT adoptions as lack of understanding of integrating into existing processes, unclear potential benefits and technical limitations. Wang et al. (2019) proposed that the main deployment obstacle is the understanding of BCT, which means that executives are hesitant about implementing it. However, as one type of SC, the application of blockchain in recycling chains received less attention (Kouhizadeh et al., 2021; Saberi et al., 2019).

2.2 | Blockchain and recycling chain

The broader context for recycling comes from CE, which links to the ecological economy proposed by Boulding (1966). The key objective of CE is to recover value from tangible goods through closed-loop reuse and recovery, which improves triple bottom line performance (Centobelli et al., 2020; De Angelis et al., 2018).

Some innovative solutions are used to improve recycling chains (Agrawal et al., 2014; Esmaeilian et al., 2018). One is 'Online recycling' or 'Internet +' recycling mode, which refers to integrations of information technologies, online models and recycling methods into CE (Tong et al., 2018). This method combines the e-commerce model to conveniently connect consumers and recyclers to form waste transactions—for example, selling secondary (waste) products to earn profits. It is believed to bring higher economic efficiency and demonstrate the advantages of price transparency (Jian et al., 2019). However, the applicability of the waste category is very limited, mainly suitable for high recycling value items, such as used laptops and smartphones. Also, it fails to form spontaneous recycling behaviour among residents since the ultimate purpose is economic (Esmaeilian et al., 2020). These limitations can be well addressed by BCT while the development of 'Internet +' recycling lays the foundation from which to explore BCT.

There are limited studies exploring BCT application in recycling, which suggests that this field is still in the nascent stage. Saberi et al. (2019) structured BCT in sustainable supply chain management (SSCM) with economic, environmental and social dimensions and pinpointed two potentials for recycling, that is, cryptographic tokens and data tracking, respectively. Similarly, Esmaeilian et al. (2020) conceptualised four capabilities for recycling, comprising green behaviour promotion, product lifecycle tracking, operation system efficiency and sustainability reporting and monitoring. Gopalakrishnan et al. (2021) developed an optimisation model to evaluate the cost of BCT-based waste management system. Also, Chidepatil et al. (2020) proposed that BCT and AI can be combined with better waste segregation and tracking, particularly for plastic waste. Howson (2020) explored the potentials of BCT to improve marine conservation via reducing ocean plastics pollution. By contrast, Taylor et al. (2020) illustrated that BCT may cause property rights issues with over transparency—for example, recyclers are reluctant to reveal their recycling information, and residents are reluctant to reveal what products they consume. In addition to the expensive investment costs, immature technical limitations still need to be improved in the recycling context, in terms of scalability, interoperability and privacy and security issues, among others

(Wang et al., 2019). Although BCT stimulates a decentralised approach to avoid the malicious intervention of third parties, the new governance structures among the BCT-based ecosystems also need to be explored (Lumineau et al., 2021). Saberi et al. (2018) also claimed that it may go through 'hype cycles' and 'peak of inflated expectations' without practical possibilities.

2.3 | Network theory

The original definition of networking refers to the relationships between individuals and organisations (Parkhe et al., 2006). The focus of 'Network Theory' is to explain the role of networks in generating economic performance (Gulati et al., 2011). The outstanding networks can provide greater access to valuable information and resources (Bellamy et al., 2014). Gulati (1998) believed that inter-organisational networks are critical components to innovative developments while dynamic benefits between network and innovation were not illustrated clearly. Pittaway et al. (2004) systematically summarised the driving effects of networking on innovation, including risk-sharing, permission for entering new markets, new technologies, gathering supplementary skills and obtaining external knowledge.

Gulati et al. (2011) integrated different network elements and proposed three levels that affect organisational network performance—these are the 'Reachability', 'Richness' and 'Receptivity' dimensions (3Rs). 'Reachability' indicates companies' abilities to connect diverse and distant business partners. 'Richness' refers to the potential resources of partners under the network framework. 'Receptivity' represents the ability to capture these potential network values across organisational boundaries. Falcone et al. (2019) referenced a case study of Alibaba Group and Cainiao, which proposed that innovative technologies are the preconditions for achieving 3Rs within the organisation based on Gulati et al.'s (2011) study.

However, the inter-organisational network needs to be formed before achieving the network outcomes. Birkinshaw et al. (2007) identified that network formations require 'identifying new relevant players' and 'learning how to cooperate'. Specifically, identifying new prospective partners may encounter 'geographical, technological and institutional' barriers, while 'ideological, demographic and ethnic factors' are the main barriers in cooperating with partners.

2.4 | Research gaps

The innovative and wide application brought by BCT could be an irreversible trend. The key 'decentralisation' characteristics of BCT and its 'transparent' and 'traceable' performance can be applicable in recycling and show excellent potential (Kouhizadeh et al., 2019; Saberi et al., 2019). However, most of the research is still in the conceptual building phase and inspired by the extension of BCT in SCM. Also, some may be over-optimistic about BCT as relying on a certain technology alone will not be a panacea. The empirical research of BCT in recycling chains is very limited (França et al., 2020). In practice, there are relevant leading organisations that have adopted BCT and realised considerable performance, but current research is lagging. Therefore, it is necessary to explore the state-of-the-art practices, analysing how BCT can be applied in recycling with what business models, involving what benefits and what the implementation barriers are.

3 | METHODOLOGY

This section presents a detailed research design. Section 3.1 introduces methodological choice, including research approach, research purpose and strategies. Section 3.2 discusses case selection, and Section 3.3 illustrates data collection and analysis. The overall research methodology flowchart can be seen in Figure 1.

3.1 | Research design

This research has an exploratory purpose to explore how BCT can be implemented in recycling with a qualitative methodological choice. Multiple exploratory case studies are conducted, which can analyse the in-depth exploration of a real-life phenomenon (Eisenhardt, 1989; Yin, 2014). The case study helps to gain insights into real phenomena and contribute to rich experience descriptions and theoretical development (Yin, 2014). In other words, this approach can answer, in detail, *how* BCT can be used in recycling chains. Also, case studies provide better understandings of the interaction between theory and empirical research (Barratt et al., 2011; Eisenhardt, 1989). Eisenhardt and Graebner (2007) pointed out that case studies are suitable for theoretical construction and are also flexible in creative theory developments. Based on network theory and BCT application practices, multiple case study design offers a good fit to elaborate existing practice with theory development. Specifically, theory elaboration was adopted to better structure theories in light of contemporary phenomenon (Voss et al., 2002)—that is, extending the understanding of network theory to explain BCT application in recycling.

3.2 | Case selections

This research follows rigorous case selection procedures with motivation, inspiration and illustration purposes proposed by Siggelkow (2007). The unit of analysis for selected cases is BCT-based recycling projects. Based on existing literature and discussions with industry experts, we conceptualised the initial criteria of case selections in Table 1. We followed the theoretical sampling method used by Eisenhardt (1989), involving as widely as possible cases (diverse cases) to fill theoretical niches (Stuart et al., 2002). The *first* criterion is that selected cases must have implemented BCT in real recycling activities. Some organisations may advocate the concept of 'Industry 4.0 for sustainability' but have not yet taken action. *Second*, cases that involved multiple stakeholders were selected as this study employs

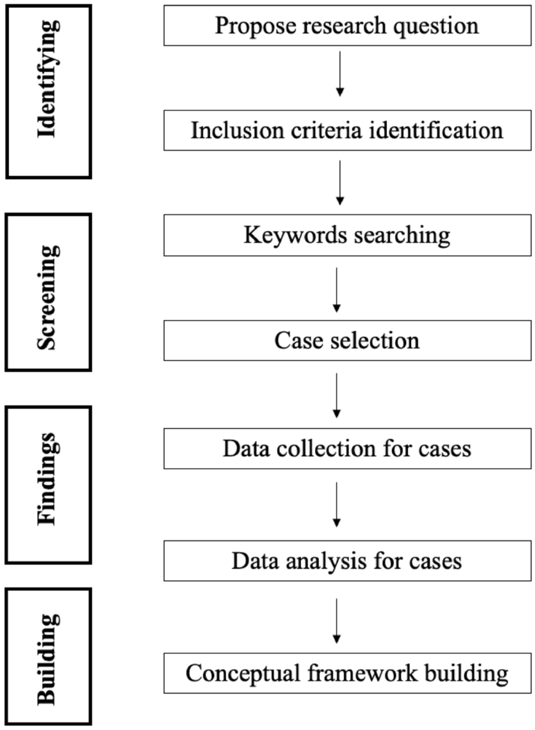

FIGURE 1 Research methodology flowchart. *Source*: Adapted from Stuart et al. (2002)

TABLE 1 Case selection criteria

Criteria	Explanation
• The case must have adopted blockchain technology in its recycling activities.	The rising trend of blockchain in sustainability attracted many organisations' practices. However, many organisations just put forward plans and do not kick-off the BCT project.
• The case must involve participation among multiple stakeholders.	Multiple stakeholders involved in activities can reflect collaboration among recycling chains and can analyse these from the recycling network perspective.
• The selected cases must reflect recycling operations of developing and developed countries' backgrounds.	The contexts of waste management are different in developing and developed countries, for example, informal collectors are common in developing countries while formal departments are in charge of waste management in developed countries.
• The case must have sufficient and accessible information.	Most blockchain-based recycling business models are in the preliminary stage. To protect property rights and knowledge, some organisations may not publish detailed information.

the network perspective to illustrate recycling chain networks. *Third*, considering the significant differences in recycling contexts between developing countries and developed countries, case selection should reflect these background differences. *Finally*, selected cases must have sufficient and accessible information to answer research questions and conduct case analysis.

Based on the above case selection criteria, we searched with keywords ‘blockchain’ and ‘recycling’ in Google pages. Initially, we found 10 targeted organisations that had strong interests in using BCT in waste management. Then we conducted initial searching by cases' official websites, prominent newspapers, professional magazines and business wire news to gain detailed information, for example, identifying their recycling chains. We found that one case just proposed the BCT designs in the promotion stage without practical applications. Also, two cases were BCT providers that just offer technical solutions without involving recycling chain networks. Furthermore, we excluded cases that only had their own published reports (e.g., white papers) but with limited supporting evidence from third parties. Finally, we identified six qualifying cases and Table 2 summarises the introduction of the selected cases.

3.3 | Data collection and analysis

This research mainly applies secondary data collection. Eisenhardt and Graebner (2007) confirmed that secondary data can serve as reliable

TABLE 2 Basic information of selected cases

Company	Headquarter	Organisation nature	Business geographic coverage	Type of waste
Plastic Bank	Canada	Social recycling enterprise	Indonesia, Philippines, Haiti, Brazil, Egypt	Household, commercial, social waste
Empower	Norway	Technical company	Europe: Norway, Sweden, Portugal, Iceland Asia: India, Nepal, Sri Lanka, Laos, Thailand, Bangladesh, Palestine Africa: Cameroon, Tanzania, Nigeria	Household, commercial, social waste (mainly plastic)
RecycleGO	USA	Recycling service and technology provider	USA and Nigeria	Commercial waste (mainly plastic)
Kabadiwalla Connect (KC)	India	Tech-driven and data-centric social enterprise	India (Chennai), Indonesia, Senegal (upcoming)	Household, social and commercial waste
CryptoCycle	UK	Technical service provider	UK	Social and household waste (mainly plastic bottles)
Agora Tech Lab (ATL)	Netherlands	Technical service provider	Rotterdam, Enschede	Household and community waste

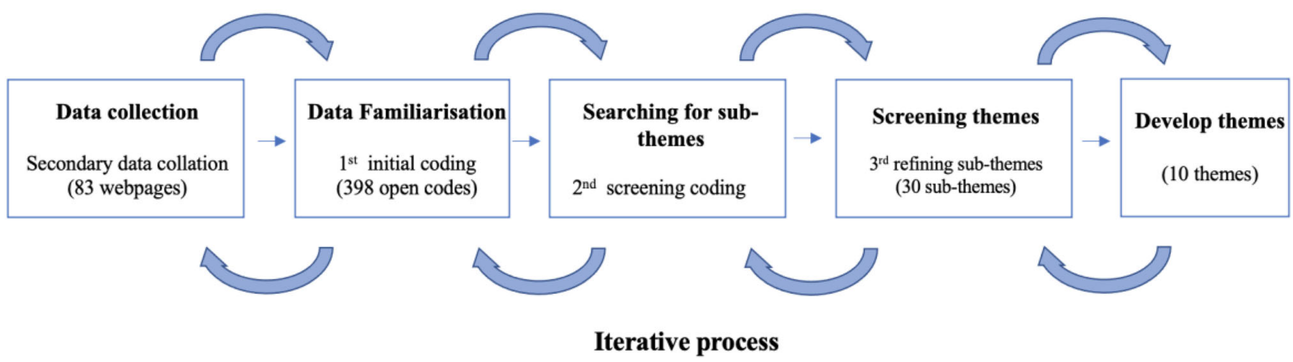

FIGURE 2 Thematic analysis process [Colour figure can be viewed at wileyonlinelibrary.com]

sources for case studies and theory development. Considering practical, financial and reputation factors, these data can also allow us to compare the development status of multiple cases at the same time point. For example, Kshetri (2018) analysed BCT solutions for SC performance with 11 cases based on secondary data. Selected cases are in the promotion stage with sufficient information, including up-to-date data which are conducive to the case study analysis. For achieving the reputation and trustworthiness of data quality, we used multiple authoritative third-party sources to avoid both source and researcher bias (Calantone & Vickery, 2010). This multiple-source includes document and survey-based data, such as archive data, public reports, blogs, prominent newspapers, professional magazines and business wire news. Data collection includes searching BCT-related information of each case company (e.g., 'Plastic Bank' AND 'blockchain') through Google. We saved all collected data of each case company into documents and finally generated 83 integrated web pages.

This research adopts 'Thematic Analysis' to analyse data, aiming to identify themes that appear in the collected data. The core is coding by providing an orderly and logical qualitative analysis method (Miles et al., 1994). Before data analysis, all secondary transcripts are grouped into documents. A within-case analysis is initially conducted before cross-case analysis to compare these six cases. In a within-case analysis, the first step is to understand the organisation's history and BCT application in recycling (see supporting information). The second step is using open codes to develop broader understandings of the benefits and barriers of BCT applications. Third, following case study analysis processes employed by Voss et al. (2002), similar code clusters are converted into sub-themes and relationships among these sub-themes are used to form final themes. The cross-case analysis compares six cases to identify different patterns and solutions, and the main findings are tabulated to explain the functions, benefits and barriers of BCT application in recycling. The overall data analysis process is shown in Figure 2.

Furthermore, this study follows rigorous validity and reliability criteria according to Yin (2014) as Table 3 shows. To achieve construct validity, this research used triangulated secondary data sources, including multiple integrations of company annual reports, business reports, blogs and news. We integrated the collected text data into the documents and conducted rigorous thematic analysis, including a systematic formation process of sub-themes and themes (details in the appendices). To ensure external validity, we communicated with

TABLE 3 Trustworthiness criteria in case research

Trustworthiness criteria	Application in this study
Construct validity	Triangulated data sources: multiple forms of secondary data integration.
Internal validity	Structured coding approach: secondary data are screened for valid content through thematic analysis and logical consistency is sought between the six cases.
External validity	Rigorous analytical generalisation; diverse case selections; discussions with experts in the recycling industry; attend online workshop of the selected case (RecycleGO).
Reliability	Case study protocol-based guidance of data collection and analysis. Secondary data are mostly based on accepted third-party data and authoritative reports.

Source: Adapted from Yin (2014).

experts in the recycling industry and participated in one workshop of the selected case. Furthermore, third-party data and authoritative reports were chosen to reduce over-reliance on internal data of cases for research reliability.

4 | CROSS-CASE ANALYSIS

Given the word count constraint, the detailed descriptions of each case and how they use BCT in their recycling activities are shown in the supporting information. The cross-case summary is shown in Appendix A. This section reports the cross-case analysis to compare overall BCT solutions in recycling and analyse relevant benefits of and barriers to BCT adoption in recycling.

4.1 | Solutions of BCT in recycling

BCT solutions vary in different backgrounds. In terms of the recycling chain, the main difference lies in waste collection practices. Waste collection in developing countries is largely undertaken by informal recycling sectors, including street waste pickers, waste merchants and waste aggregators [e.g., KC]. They usually collect waste door-to-door or pick from street bins without fixed collection times and then resell it to next-level recyclers in exchange for monetary payment. Although the informal groups still use primitive recycling equipment, they make a significant contribution to municipal waste collection; for example, they can even collect more than 80% of municipal waste (Chen et al., 2018). In developed countries, waste collection is mostly organised by municipal departments, which usually collect household and street waste in a fixed and timed manner and then deliver it to recycling centres for further processing, but only limited types can be recycled. To ensure the efficiency of subsequent sorting and processing, residents are required to undertake the task of waste sorting. Based on selected cases, BCT empowers great performance for recycling chains based on these different backgrounds but without changing original recycling chain processes. It should be noted that most cases are in the pilot phase, and few cases have fully operated in some regions [Plastic Bank, Empower]. In general, three functions are identified from the six cases: Tokenisation, Waste flow tracking and Recycling chain integration.

4.1.1 | Tokenisation

One distinctive function is tokenisation which has been adopted by five cases. It serves as the main approach to motivate participation. Users are required to deliver collected waste to appointed recycling sites and separate waste into smart bins according to waste type. This process is usually empowered through sensors and smartphones. By scanning codes, waste information (e.g., waste type and weight) will be uploaded to users' digital accounts. Then, users will obtain corresponding digital currency rewards according to fixed premium prices. Digital currencies can be exchanged for physical consumption in local supermarkets [Plastic Bank] and public services, such as insurance and tax credit [Agora Tech Lab], and can also be converted into cash and local currencies [Plastic Bank, Empower, CryptoCycle, KC]. The tokenisation function has targeted users. It can represent both business-to-business (B2B) and business-to-customer (B2C) business models, and some cases contain both [Plastic Bank, Empower, KC]. The B2B model targets waste aggregators or recycler merchants while the B2C model provides incentive solutions for individual users such as citizens, and individual informal waste pickers.

4.1.2 | Waste flow tracking

Waste tracking is reflected in all six cases. By scanning the attached QR codes, the traceability feature of BCT provides transparent visual recycling processes for all members of the recycling chain (Esmaeilian et al., 2020). Although different stakeholders may have priority access rights, for example, data input, the immutability of BCT can ensure that the recycling information is trustworthy. The tracking function is similar to the possible application in the food SC, which helps to reduce fraud and malicious middleman tampering (Wang et al., 2019). In recycling, traceability can show manufacturers the source of waste, particularly for manufacturers that have quality requirements for recycled materials, for example, plastic waste [Plastic Bank]. Another potential solution of traceability is to encourage positive recycling behaviour. The BCT-enabled recycling chain can show the lifecycle of collected waste, in which recycling chain members will try to maintain high recycling rates rather than send the waste to landfill [CryptoCycle]. Furthermore, the tracking feature is applicable to provide advanced SC solutions by being combined with other technologies. For example, RecycleGO uses BCT to offer advanced waste logistics solutions with data analysis capabilities supported by Big

Data analysis. It not only optimises transport routes for waste collection but also demonstrates recycling flows (Chen, 2020).

4.1.3 | Recycling chain integration

BCT sheds light on unique strengths for recycling chain integration as traditional recycling chains are fragmented and linear. In developed countries, most waste is landfilled or dumped to other countries for processing with limited recycling utilisation (Wen et al., 2021). Also, recycling chain members are scattered since they may evade recycling responsibility. For example, consumers believe that recycling should be handled by relevant departments while manufacturers are unwilling to bear excessive recycling costs. In developing countries, the recycling efficiency of informal recyclers is inferior, and they opt for the ultimate goal by reselling waste to make profits (Hande, 2019). In other words, both backgrounds show fragmented limitations while selected cases illustrate how focal companies leverage BCT to integrate multiple recycling chain members. BCT can facilitate cooperation with powerful technical providers, such as the partnership with IBM [Plastic Bank] and manufacturers [Empower]. More importantly, it shows a successful incentivisation manner to encourage participation—that is, engaging waste collection with residents [ATL, CryptoCycle] and informal sectors [KC, Plastic Bank, Empower]. With the contiguous promotion, some cases attract cooperation with influential organisations, for example, Ellen MacArthur Foundation [Empower], and attract support from municipal departments [ATL].

4.2 | Benefits of BCT in recycling

The coding processes of thematic analysis of BCT benefits in recycling are detailed in Appendix B, which helps to address corresponding traditional recycling issues. Figure 3 shows themes and sub-themes of the BCT benefits.

4.2.1 | Eco-friendly

Eco-friendly is the primary advantage, and six cases demonstrate different levels of environmental performance, for example, stop waste flows into landfills or oceans, promote CE and combat climate change. Specifically, being eco-friendly means achieving remarkable recycling performance. For example, Plastic Bank attracted more than 17,000 waste collectors through public outreach, with a total of 28.8 million kilograms of plastic recycled by 2021. It even achieved the milestone of stopping 1 billion plastic bottles from flowing into oceans (Henkel, 2021). Also, in the KC case, it is expected to reduce the local landfill volume by 70% (Hande, 2019). The BCT-based recycling platform of Empower achieved a 97% recycling rate of plastic bottles by incentivising waste collection (Myrer, 2020). The Reward4Waste programme powered by BCT can supplement original deposit refund by achieving a 90% recycling rate of plastic bottles [CryptoCycle]. In addition to empowering waste values, the BCT-based model can improve waste sorting at the front-end. For example, KC designed smart bins called 'Urbins' which covered 1500 households with waste-sorting guiding and education (Hande, 2019).

4.2.2 | Stimulate participation

The recycling performance largely depends on participation. BCT can stimulate participation from three levels: (i) attracting participation from users; (ii) providing entrepreneurial opportunities for recyclers; and (iii) co-working with other organisations (Katz, 2019). The incentive of token rewards creates great potentials for waste collection at the front-end of recycling chains. For cases operating in developing countries, the engagement of informal sectors significantly increases waste collection volume [Plastic Bank, Empower, KC]. Since BCT ensures a stable and trustworthy recycling business, informal pickers are more willing to join, for example, Plastic Bank engaged more than 17,000 individual collectors across five countries (Henkel, 2021).

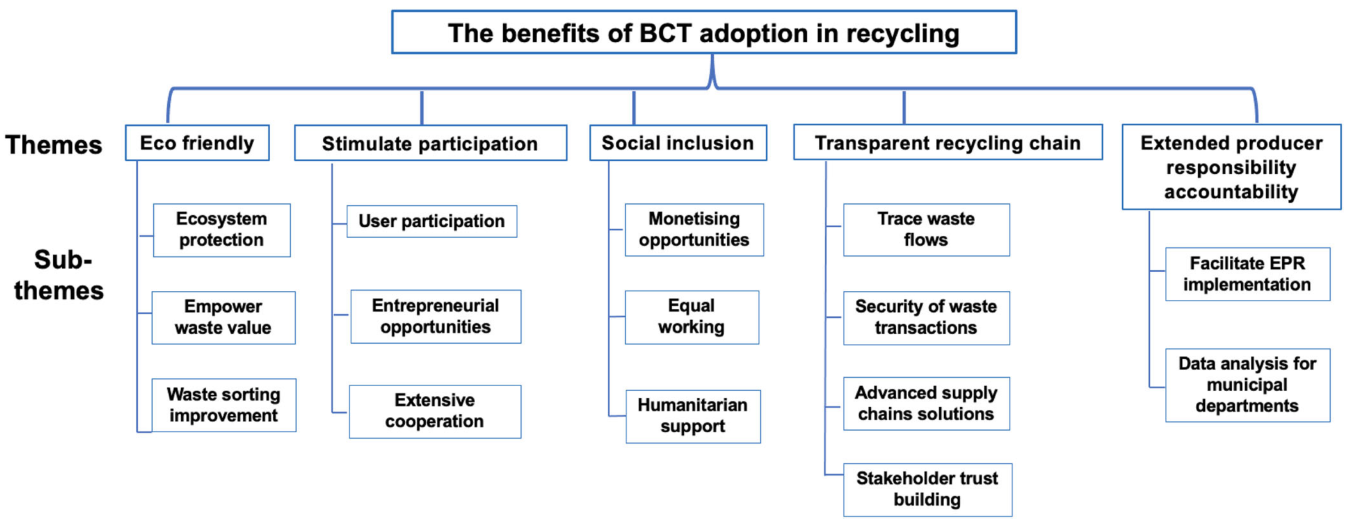

FIGURE 3 Themes and sub-themes summary of BCT-recycling benefits [Colour figure can be viewed at wileyonlinelibrary.com]

Informal waste sectors even account for more than 80% of local waste collection [KC]. For cases operating in developed countries, BCT offers residents convenient waste sorting, such as the use of a deposit return scheme by CryptoCycle. Digital points can be used to buy physical products (supermarket shopping), be exchanged for public services (transportation, taxes) or be converted into local currency [e.g., ATL].

Also, BCT creates entrepreneurial opportunities for recyclers. Empower encourages local recyclers to establish their own recycling business with a local ownership model. For the KC case, the BCT solution enriches the local hierarchical recycling model (level 0 street picker, level 1 waste collector, level 2 waste trader). It elucidates how BCT can respond to circular business model promotion under the emerging trend of 'Industry 4.0' (Kumar et al., 2021). Furthermore, it can attract cooperation among industries, maintaining close contact with their partners, including waste providers, retailers and technology providers. For example, as the largest BCT recycling pioneer, Plastic Bank has attracted cooperation with technology provider IBM, as well as other influential brands such as Henkel and SC Johnson. Other cases also demonstrated the impact of partnerships with leading NGOs, such as the Ellen MacArthur Foundation [KC, Empower].

4.2.3 | Social inclusion

This model provides social inclusion for informal waste sectors with monetising opportunities [Plastic Bank, Empower, KC]. The reward fees for waste collection are implemented according to standard price mechanisms, thus ensuring equal opportunities for waste collection. Most waste pickers in developing countries are vulnerable people with low living standards and unsanitary working conditions (Peshkam, 2019). In the KC case, the survey conducted by Hande (2019) showed that recycling profits per month by waste pickers and larger waste aggregators can range from $270 to $1500 [KC]. Equal working opportunities provide employment opportunities for unskilled groups (e.g., most street pickers are elderly). Also, token services can promote financial inclusion for waste pickers who do not have bank accounts (Mok, 2018). For example, Empower introduced digital point-based financial lending, which leads to more financial services for waste pickers and supports them to start micro-businesses (Clawson, 2018). Additionally, it offers humanitarian support, which can be reflected in reducing poverty through charitable donations [Empower, ATL].

4.2.4 | Transparent recycling chains

Transparent recycling chains are embodied in four aspects; these are 'trace recycling flows', 'security of waste transactions', 'advanced supply chain solution' and 'stakeholder trust-building'. BCT ensures the visibility and transparency of whole recycling chains, which helps stakeholders to monitor the entire processes from collection to final remanufacturing and to avoid middlemen interventions (Clawson, 2018). For example, in RecycleGO, BCT was adopted in the beach clean-up project in Miami to track plastics along the beach to ensure collected plastic bottles are recycled. By scanning the QR codes attached on plastic bottles, customers can visualise the recycling information of the lifecycle of reused products (Chen, 2020). Also, the BCT-based platform guarantees data integrity and security of recycling data (França et al., 2020), which can combat fraud, and losses in receiving or exchanging the rewarding credits. In the CryptoCycle case, BCT powers the Deposit Return Scheme, which can guarantee that reclaim of a deposit per container cannot be triggered more than once due to unique codes (Gallacher, 2019). Also, as an approach, it acts as an initiative whereby consumers can spontaneously conduct recycling via smartphones without costly reverse-vending machines.

Also, it provides a digital approach to connect multiple recycling processes. It can reduce the inefficiencies that existed in traditional recycling chain supervision, such as cumbersome paperwork involving multi-agency verification (Saberi et al., 2019). Moreover, this model provides advanced innovative SC solutions, which are reflected in RecycleGO. RecycleGO combines Big Data analytics and BCT to provide optimised waste transportation routes for hauliers. In waste transportation, waste collection routes can be intertwined according to different locations and daily amounts. RecycleGO designed 'Carter Performance Management software' for tackling this issue. It can digitise shipping routes and streamline the operations of hauliers—for example, coordinate on-demand pickups and real-time transportation tracking (Chen, 2020).

4.2.5 | Extended producer responsibility accountability

Traditionally, there are no standards to assign responsibility to recycling chain members. Although it was improved by the extended producer responsibility (EPR) system, which defines the major responsibilities of producers, the actual implementation is challenging. For example, manufacturers believe that consumers should bear part of the recycling obligation, and EPR is only applicable to limited waste categories. The BCT-based system creates an accessible recycling chain, which can clarify the impact of different members by adding values for consumers and focal companies (Staub, 2019). Specifically, the BCT recycling model requires manufacturers to demonstrate the lifecycle of products from the 'cradle'. This mode enables recyclers and manufacturers to strictly follow EPR and comply with promotions of environmental protection policies [Empower, RecycleGO, KC]. Also, the BCT-based platforms can record waste information to municipal authorities for further data analysis via rich channels [CryptoCycle] (Gallacher, 2019).

4.3 | Barriers to BCT application in recycling

Although the BCT applications in recycling can achieve considerable recycling performance, there are several barriers to implementation.

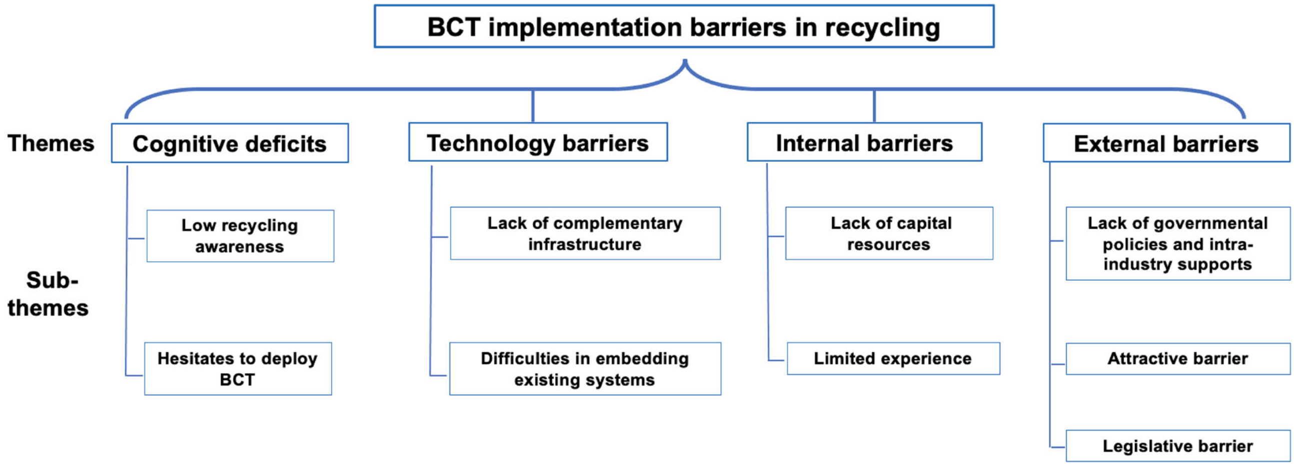

FIGURE 4 Themes and sub-themes of BCT-recycling implementation barriers [Colour figure can be viewed at wileyonlinelibrary.com]

Based on the cross-case analysis, four implementation barriers are identified. The coding processes of sub-themes and themes of BCT recycling barriers are detailed in Appendix C. Figure 4 shows the overall sub-themes and themes of BCT implementation barriers.

4.3.1 | Cognitive barrier

Cognitive barriers include cognitive deficits of recycling and BCT perceptions. The deficiency of recycling consciousness is reflected in low levels of citizens' cognition, the lack of recycling knowledge and limited interest in waste sorting. Also, the BCT cognitive barrier is a significant factor affecting deployment. Some senior managers lack understanding of BCT or lack support for effective deployment. Alternatively, some organisations are waiting for the results of pioneers' deployment before deciding on the final adoption (Holland, 2020).

4.3.2 | Technology barrier

Technological barriers are the technical defects of BCT and the compatibility of integration into existing recycling ecosystems. Currently, most of the recycling businesses still follow the traditional linear model, although some innovative solutions (e.g., 'Internet +' recycling) are emerging (Tong et al., 2018). The crucial barrier is how this creative technology fits into traditional recycling chains and informal sectors. Also, the selected cases show that the BCT platform needs continuous updates and maintenance. For example, the application software developed by technical providers can support the essential operations, but underlying technical applications need to be iteratively updated (Myrer, 2020). In other words, focal companies may need external technical experts to maintain BCT implementation at additional cost.

4.3.3 | Internal barrier

Internal barriers refer to the barriers within organisations. Most of the selected cases are technology providers or companies with superior resources but are still limited by capital and technical capabilities. For example, the CEO of RecycleGO believed that financial burdens limited the company's ability to expand diverse BCT capabilities (Chen, 2020). Although these companies are pioneering companies with innovative spirits, they still face various unknown challenges and lack of BCT-based business model experiences.

4.3.4 | External barriers

External barriers occur when focal companies may lack cooperation from intra-industry and governmental policies, involving legislative barriers. Specifically, the collaboration between industries involves mutual support among them. Recycling may be subject to industry competition—some is even controlled by local monopolies—making it difficult for other recycling companies to operate new businesses (Katz, 2019). Also, recycling businesses are subject to policy constraints set by municipal departments, including strict control over the types and information of recycling (Reflow, 2020). Although tokenisation can stimulate potential participation rates, token functions and exchange mechanisms need further innovation to attract more users. Furthermore, tokenisation services involve virtual currency, and more explicit regulatory support is required on how to exchange digital points for public services and convert for local currencies.

5 | DISCUSSION

This section critically analyses the key findings from our study with those from the reviewed literature and applies 'Network theory' from the 'Reachability', 'Richness' and 'Receptivity' perspectives (Gulati et al., 2011) and network formation barriers to deepen our findings (Birkinshaw et al., 2007).

From an operational background perspective, we found that the operating models vary under different recycling networks. Based on waste collection channels, informal waste pickers play an important role in developing countries. In developed countries, waste collections are conducted by local recycling enterprises or social welfare organisations. The findings show that BCT can be operated in both developing and developed countries, which is in line with the promotion of BCT in CE proposed by Kouhizadeh et al. (2019). Specifically, it can integrate informal sectors to improve employment situations and working conditions and even provide basic living needs in developing countries [Plastic Bank, KC, Empower]. This contradicts the conceptual opinion by Saberi et al. (2019) who proposed that BCT generates great potentials in economic and environmental sustainability dimensions than in social dimensions. This phenomenon can be explained by the exceptional monetising opportunities. In developed countries, CryptoCycle has developed the BCT-based solution embedded on the original 'Deposit Return Scheme', which shows great improvement in citizens' participation. Also, ATL shows that tokens have fruitful functions, for example, public transportation service.

Overall, this model further deepens existing waste management solutions, for example, 'Internet +' recycling. It helps to create mutual trust and multi-stakeholder interconnections among recycling networks. Inter-organisational networks emphasise combinations of organisational and partnership relationships, including associated information, resources and innovation capabilities (Borgatti & Foster, 2003). According to Inter-Organisational Network theory, the interconnections empower various resources that can influence organisational performance outcomes and behaviour (Kim & Zhu, 2018). The recycling network built through BCT can utilise existing resources to achieve transparency, traceability and diversified solutions among recycling networks. Six cases show that it can reorganise traditional linear patterns and restructure other members (e.g., informal groups) involved in the recycling chain. Through the construction of the BCT platform, the recycling chain can be extended to a more comprehensive range of stakeholders and tighter network architecture. Therefore, we propose:

> **Proposition 1.** The recycling network built by BCT shows considerable recycling performance, but functions will vary depending on different operating economic backgrounds.

The following sections further discuss the detailed networking effects on recycling performance, including 'Network reachability', 'Network Richness', 'Network Receptivity' and 'Network formation barriers'.

5.1 | Network reachability

'Reachability' refers to the ability to reach distant business partners through interconnectivity (Gulati et al., 2011). In six cases, network reachability is reflected in the enhanced cooperation among recycling chain networks. Traditional recycling chains are fragmented and linear, while BCT can achieve closer collaboration and involve extensive stakeholders, as Appendix B shows. Also, traditional recycling chains are dyadic—that is, involving recyclers and waste collectors without multi-level cooperation. The BCT recycling model can engage external members. Street collectors from marginalised populations can be integrated into recycling chains with digital identities [KC], as well as municipal sectors [CryptoCycle, ATL].

Moreover, broader coverages of the network constructed by BCT can strengthen cooperation between focal companies and remote stakeholders. This solution builds a platform with a sense of user participation. It attracts waste collection from informal sectors, encouraging citizens to engage in waste sorting and providing recyclers with a considerable waste amount. With greater transparency, stakeholders will be more willing to reach other members to collectively contribute to triple bottom line efforts. Therefore:

> **Proposition 2.** The BCT-based recycling model can integrate various stakeholders and restructure recycling chains through network reachability.

5.2 | Network richness

Gulati et al. (2011) illustrated that organisations could acquire potential resources from their partners through 'network richness'. This study shows that 'network richness' can be realised by broader user groups. The findings illustrate that BCT functions include tokenisation services, waste flow tracking and recycling chain integration, which further proves the feasibility of BCT to improve CE performance (Saberi et al., 2019).

The tokenisation functions of BCT can add unique values for achieving recycling network engagement. This study identified fruitful token functions, including physical consumption, local currency exchange or public services. Also, token services target different users, including B2B and B2C solutions. Specifically, the B2B model targets recyclers and waste collectors (e.g., KC) while the B2C model is encouraging individual recycling behaviour through cryptocurrency rewards from the individual user perspective, such as city dwellers [Empower, CryptoCycle, ATL] or waste pickers [KC].

Also, BCT can bring waste flow tracking and advanced SC functions due to the traceability feature. In general, it can encourage waste sorting and build trust among recycling networks. In waste tracking, BCT can transparently display waste flows, from waste collection to final disposal (Taylor et al., 2020). The direct impact is that the recycling members will fulfil their recycling responsibility—for example, residents who conduct waste sorting at front-end and back-end processing will seek recycling solutions over incineration or landfill. Also, malicious tampering will be restricted since no third-party audit is required for waste data recording. As a result, the BCT solution can form a trust-free mechanism among recycling chain networks. It is also consistent with Wang et al. (2019), who proposed that BCT can support information interaction and achieve openness, transparency and security among stakeholders. Furthermore, BCT provides advanced data analysis capacities for recycling network members. The advanced solution is the optimisation of waste transportation routes in the case of RecycleGO, which can establish a chain of custody among recycling chain members.

Overall, the integrated recycling network can realise various functions which can attract active participation. Along with recycling network expansion, the cooperation of stakeholders can deepen the robustness of network systems. The BCT-based recycling network enables waste collectors, recyclers, manufacturers and end-users to display waste flow transparently. It can reduce the illegal intervention of the middlemen, which can increase mutual trust among recycling networks.

> **Proposition 3.** BCT solutions provide fruitful functions that can add richness to the recycling network and increase trust between members through transparency and traceability.

5.3 | Network receptivity

Gulati et al. (2011) emphasised that network receptivity is related to the actual value extracted from the network, including how to maximise the utilisation of network resources and facilitate network resource flows. Mutual benefits among recycling chain stakeholders are described in Section 4.2; these benefits further strengthen recycling chain integration among networks.

The eco-friendly component is the most fundamental advantage, which further verifies that CE can be promoted by technological-driven solutions (Awan et al., 2021). Token services are an indispensable way to increase user interest in participation, particularly in low recycling awareness regions. This model presents win–win opportunities, whereby users can be rewarded through recycling behaviour and recyclers can conduct more efficient waste collections, which can effectively mitigate potential barriers (Kouhizadeh et al., 2021). Social inclusion is mainly reflected in developing country cases by integrating informal waste sectors which can achieve sustainable development goals (França et al., 2020). It also demonstrates an innovative recycling business model for developed countries. Stimulating participation reflects the fit of the model for different stakeholders, for example, entrepreneurial opportunities for local recyclers. Transparent recycling chains can enhance trust among stakeholders and stimulate collaboration with other organisations. It can show waste flows to stakeholders and ensure the safety and authenticity of recycling data. It supports Kshetri's (2018) argument that BCT can prevent SC risks such as data tampering and illegal agent behaviour. The findings also provide new insights into EPR, which complements the role of innovative technologies in promoting EPR policy (Esmaeilian et al., 2020).

Overall, recycling network members can achieve joint mutual benefits from 'network receptivity'. Waste collectors can earn economic returns; recyclers can collect waste efficiently; and retailers can show customers the full product lifecycle through BCT, ensuring full transparency. These practical benefits can be verified with the promotion of recycling chain integration, which in turn enhances network robustness. This finding corroborates the ideas of Falcone et al. (2019) who suggested that multiplexity collaboration can enhance trust and commitment among the network partners. Thus, we propose:

> **Proposition 4.** The BCT recycling model can achieve mutual benefits for the recycling chain stakeholders, which can deepen cooperation with partners and enhance recycling chain robustness through network receptivity.

Nevertheless, although the three dimensions can verify the driving effects of achieving network resources, they cannot explain the networking process, which can be supplemented by the network formation barriers theory by Birkinshaw et al. (2007).

5.4 | Network formation barriers

The network formation includes integrating original fragmented recycling networks into connected BCT-based networks. We identify four types of barriers based on the cross-case analysis—cognitive, technical, internal and external barriers. *Cognitive* barriers arise from uncertainty in new technology applications and the lack of recycling awareness. This research further supports Wang et al. (2019) by adding recycling context considerations; they proposed individuals' negative perceptions of using disruptive technology. Also, the lack of awareness of recycling may limit users' participation. The cognitive barriers can correspond to the 'ideological barriers' proposed by Birkinshaw et al. (2007). Specifically, some organisations aim at making profits rather than realising environmental and social responsibilities and benefits. They may be unwilling to transparently expose their recycling chain to stakeholders or customers, which in turn affects the formation of inter-organisational networks.

Technical barriers mainly refer to the immaturity of BCT, such as the collision of BCT with existing systems, which needs supporting technical infrastructure (Saberi et al., 2019). Also, findings show that BCT adoption usually needs to be combined with other technologies, such as Cloud technology and IoT technology [RecycleGO, KC], which proves that the innovation opportunities usually appear at the intersections of multiple technology fields (Birkinshaw et al., 2007).

Internal barriers involve within-organisation factors, such as lack of internal development capital and experience. This corresponds to the findings of Hastig and Sodhi (2020) which demonstrated that converting conceptual ideas of BCT into practice is financially constrained. Top managers may be reluctant to take risks on disruptive BCT applications and look forward to becoming the 'later-mover'. Although token rewards can encourage potential participation, incentives may be constrained by limited attractiveness or complicated rewarding procedures (e.g., users are required to have smartphones to download apps and register digital accounts). Also, BCT in this context

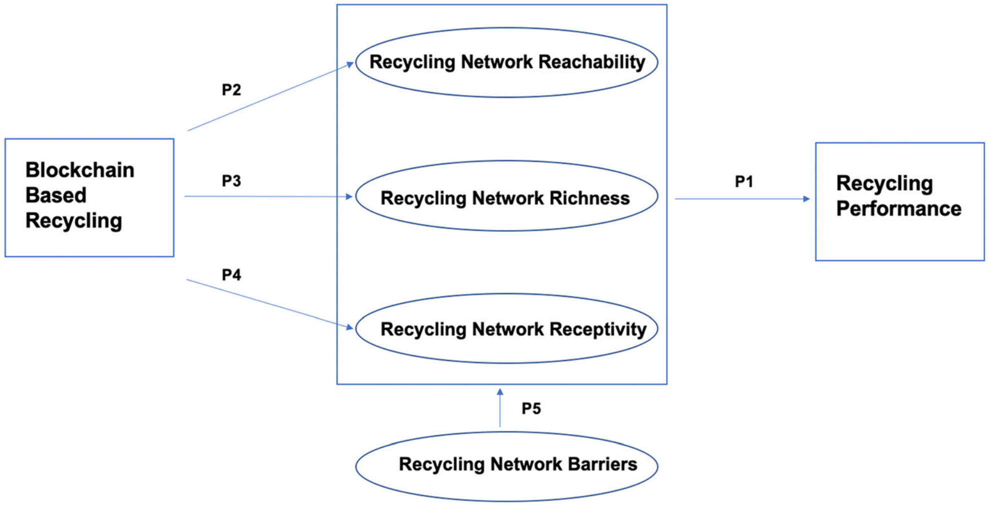

FIGURE 5 Conceptual framework of BCT adoption in recycling [Colour figure can be viewed at wileyonlinelibrary.com]

lacks development experience as existing practices are led by pioneer companies that still face uncertain challenges.

External barriers consider factors outside the focal companies. The innovative finding is that institutional constraints may exist in the token services, which extends the external environmental barriers of BCT application proposed by Saberi et al. (2019). There is still ambiguity over how tokens can be used to offset physical consumption and local currency exchange. Since this mode is in the initial stages, criminals may take advantage of the current legal loopholes such as engaging in financial fraud and illegal trading (Du et al., 2020). Birkinshaw et al. (2007) proposed that 'ethnic barriers' originate from cultural differences that affect network formations. Since most of the six cases operate in multiple recycling backgrounds, these focal companies inevitably encounter cultural and ethnic barriers, such as local culture shocks. Thus, we propose:

> **Proposition 5.** The network formations of the recycling chain are subject to multiple barriers, which may affect inter-organisational network performance.

Based on the above discussions, we propose the conceptual framework of BCT adoption in recycling in Figure 5. In general, the BCT-based recycling networks can enhance recycling performance (P1) based on the three functions of BCT, which can be further explained by 'Network Reachability (P2)', 'Network Richness (P3)' and 'Network Receptivity' (P4). However, a BCT-based recycling network needs to overcome various barriers in order to maintain expected recycling performance (P5).

6 | CONCLUSION

This research explored how BCT can be applied in recycling and addressed the related benefits and adoption barriers. Through case screening, we selected six pioneer companies for cross-case analysis. The findings indicate that the BCT model can run smoothly in different economic contexts with three functions: token services, waste tracking and recycling chain integration. *Token services* include encouraging recycling participation of waste collectors, recyclers and end-users by delivering rewards including digital credits, *waste tracking* can provide the visibility of waste lifecycles and *recycling chain integration* can enhance recycling chain network collaborations. The benefits of this model include 'Eco-friendly', 'Stimulate participation', 'Social inclusion', 'Transparent recycling chains' and 'Extended producer responsibility accountability' factors. However, this innovation model is still mostly in the pilot stage with cognitive, technical, internal and external barriers.

This research is one of the first empirical studies on 'BCT and recycling' by exploring worldwide pioneering recycling companies. It further supports the application of BCT in SSCM and responds to Saberi et al. (2019) by verifying the feasibility of recycling. Through cross-case studies, the multiple benefits and the barriers in implementation are illustrated in detail through rigorous thematic analysis. Second, this research combines 'Network Theory' to explore the role of BCT in recycling. The BCT-based recycling network allows recycling chains to integrate multiple stakeholders and form collaborative networks. Also, this research extends the Inter-Organisation Network theory of 'Reachability', 'Richness' and 'Receptivity' (Falcone et al., 2019; Gulati et al., 2011) by adding network formation barriers. In particular, it provides specific BCT adoption barriers in recycling chains.

6.1 | Managerial implications

This study shows managerial implications for practitioners and policymakers in the recycling industry. In general, it shows that the traditional recycling industry can be driven by innovative technologies, which can significantly improve recycling chain performance. It enriches the understanding of CE practices by using 'Industry 4.0' technologies with triple bottom line considerations. This research can also motivate pioneers to embrace BCT in their recycling business or revolutionise current practices. Specifically, it can further deepen existing recycling solutions (e.g., 'Internet +' recycling model) by stimulating recycling participation, forming the recycling chain network and tracking the waste lifecycle. Industry pioneers who propose to use BCT can consider circular business models embodied in cross-case studies, for example, introducing token services to encourage participation. This research presents existing functions and clearly lists benefits and barriers, which can facilitate practitioners in decision making regarding BCT applications and overcome potential barriers. Furthermore, fruitful benefits of using BCT may convince policymakers to propose supporting policies to encourage further exploration.

6.2 | Limitations and future directions

This research has a few limitations. First, BCT application in recycling is still in the pilot phase while the case selections are pioneer companies. There may be other cases that can provide extra functions, benefits or barriers which may not be covered in this research. Also, only cases that have adopted BCT were selected, which cannot provide details of adoption behaviours. Second, secondary data collection may not be in-depth enough to explore implementation processes and long-term BCT performance. It cannot reflect perceptions of recycling chain stakeholders which may have different network effects. Finally, the proposed framework is based on the network perspective with selected cases, which may not be suitable for BCT applications in other sectors.

Several future research directions are worth exploring. First, our research findings can be expanded to other recycling cases to seek unique BCT functions, relevant benefits and barriers. Second, the governance structure of BCT can be further explored since not all BCT projects follow a pure decentralised governance manner. The BCT-based recycling solution also involves how recycling chain members maintain network collaboration. In addition, it is necessary to analyse the long-term benefits and potential drawbacks of BCT adoption because BCT just plays the role of an 'enabler' rather than being the 'panacea'. Furthermore, in-depth studies, for example, using interviews and quantitative empirical and analytical modelling, can verify and extend the proposed framework in this research.

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SUPPORTING INFORMATION

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APPENDIX A

CROSS-CASE SUMMARY

Cases	BCT application status	BCT-based stakeholders	BCT solutions
Plastic Bank	Fully implemented; several pilot trial to adjust with local contents	(1) Full-time collectors; (2) medium collectors; (3) collection centres; (4) recycling plants; (5) manufacturers; (6) local entrepreneurs and communities; (7) end users; (8) blockchain technical provider: IBM.	(1) Developed Plastic Bank App to conduct waste inventory tracking for social enterprises, offline transactions and secure E-wallet for users. (2) Plastic Bank encourages both consumers and waste pickers to join plastic recycling initiatives and offer tokens, which can be exchanged for public services (e.g., healthcare and supermarket shopping) or local currency.
Empower	Majority in pilot; fully implemented in India, Nigeria	(1) Local partner (waste providers) waste pickers; (2) waste aggregator; (3) collection points; (4) retailers; (5) recyclers; (6) manufacturers; (7) cooperation companies; (8) end users.	(1) Built BCT-enabled global deposit system by empowering plastic values (every kilo of waste = 1 token = $1), end users and waste pickers can collect rewards in digital tokens *(EmpowerCoins)* or local currencies when they deliver their waste and present their QR codes. (2) Provided tracking system for recyclers, which shows waste collection, tracks and manages recycling flows, and ensures waste transaction safety through BCT; and runs the digital inventory system which shows wastes flows throughout the whole supply chain. (3) Provided added value for plastic waste and branding value propositions for companies through recording recycle footprints and issuing the BCT-based certificate.
RecycleGO	Pilot	(1) Hauliers; (2) recycling centre; (3) recyclers (work with recycling company Wecyclers); (4) manufacturers; (5) retailers (business and property owners).	(1) Provided BCT-based recycling platform includes recycling management and supply chain solutions for recyclers, hauliers, local departments, building trust among stakeholders. (2) For hauliers: developed *Carter Performance Management software* and dual-system logistics Apps '*Mission Control*' and '*Chariot*', which enables transportation managers to digitally manage customers, bills and vehicles and customise the best routes based on traffic. (3) For recyclers: created BCT-based '*SideKick App*' for recyclers to provide on-demand pickups and real-time materials tracking through decentralised ledgers' transparency and accountability. (4) For municipalities: provided BCT-based platform for municipalities to monitor recycling process and legalise recovery incentive scheme such as deposit return programmes.

(Continues)

Cases	BCT application status	BCT-based stakeholders	BCT solutions
Kabadiwalla Connect	Pilot	(1) Residents; (2) informal street waste pickers; (3) level 1 aggregator; (4) level 2 aggregator; (5) scrap dealers ('Kabadiwalla'); (6) neighbourhood waste collections; (7) recycler (repressors); (8) manufacturers.	(1) Leveraged existing informal waste infrastructure in collection and integrated them into the mainstream waste management system through decentralised solutions. (2) B2C solution: developed smart bins ('Urbin') which can transfer waste-full messages to waste aggregators through sensors and record recycling activities through scanning codes; and created the 'RecyKle' app which provides garbage classification tips and connects waste aggregators ('Kabadiwallas') for residents by mapping technology. (3) B2B solution: developed a survey app that connects to a broader range of scrap traders, logistics platforms and municipalities through its own material recovery facilities.
CryptoCycle	Pilot	(1) Consumers; (2) retailers; (3) recycling sites; (4) recyclers; (5) manufacturers; (6) regulators.	(1) Provided solutions for two projects: 'Reward4Waste' (R4W) and 'NappyTrac' through BCT solutions. (2) R4W: Applied BCT to the traditional Deposit Return Scheme (a small deposit is required for the purchase of drinks in plastic bottles and the deposit will be returned when the bottles are recycled) by BCT-based app, which create codes for each bottle, provides transparent tracking information, rewards users for recycling and also provides clean waste streams for manufacturers. (3) 'NappyTrac': The similar solution to R4W, developed *'NappyTrac App'* to truck disposable nappies transparently and encourage nappy recycling by providing tokens.
Agora Tech Lab	Pilot	(1) Urban dwellers; (2) communities; (3) recycling centres; (4) recyclers; (5) manufacturers; (6) municipal departments.	(1) Created BCT-based participatory waste management framework to help municipalities separate waste and monitor waste processes. (2) Offered technical support for creating an ecosystem which records waste management transactions for urban dwellers. (3) Rewarded citizens' recycling activities by tokens which are exchanged for public services (e.g., free public transport) and governmental services (e.g., tax reduction).

APPENDIX B

THE BENEFITS OF BCT IN RECYCLING

BCT benefits (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
Eco-friendly	(1) Ecosystem protection	Protect ocean pollution; stop flows of plastic waste into oceans; increase sustainability through LC, save ocean crisis, clean waste streams for manufacturers; streamline the management of recyclables; indirect contribution to climate change.	Based on the blockchain recycling solution, Plastic Bank has attracted more than 18,000 recyclers and collected about 17 million tonnes of the recycling waste in 2020, greatly reducing the amount of garbage that ends up in the ocean. [Plastic Bank] Empower's proposed blockchain-based global deposit system enabled Norway to achieve a recovery rate of 97% for plastic bottles. [Empower]. The supply chain solutions provided by RecycleGO can optimise the path of waste transport and reduce carbon emissions during transport through BCT. [RecycleGO] The BCT-based operation model provided by KC effectively integrates the informal waste sector of Chennai city, which is expected to reduce the landfill volume by 70%. [KC] The R4W programme can supplement the original deposit refund programme and achieve 90% increase the recovery rate of plastic bottles recycling rates. [CryptoCycle] The participatory waste management system provided by ATL can better track waste flows from producers to the landfill, which can indirectly improve climate change. [ATL]	https://plasticbank.com/our-impact/ https://www.ashokanordic.org/post/meet-empower-a-changemaker-how-to-tackle-plastic-waste-using-blockchain https://solve.mit.edu/challenges/RethinkPlastics-en/solutions/15640 https://impakter.com/exploring-informal-waste-management-an-interview-with-siddharth-hande/ https://www.cryptocycle.co.uk/ https://reflowproject.eu/best-practices/agora-tech-lab-creating-circular-economies-by-rewarding-responsible-behavior/
	(2) Empower waste value	Preserve plastic value for CE; set plastic premium rate; keep waste value for the whole lifecycle; improve the original value of plastic waste.	Plastic Bank initiated *'Social Plastic Coins'* for adding values for plastic waste. [Plastic Bank] Empower built a BCT-based platform which can record recycling behaviour, empower plastic waste value and reward people (every kilo of waste = 1 token = $1). [Empower]	*The Empower token, the EMP can be converted into the local currency. We piloted it previously at the rate you mentioned, but now it depends on the local contexts. Empower will agree on a price with the local collection point. (Legal Counsel of Empower)*

(Continues)

BCT benefits (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
			CryptoCycle improved conventional DRS and encrypted codes for every plastic bottle to reward recycling. [CryptoCycle] ATL provided a recycling-point model for urban waste solution, which can use plastic waste from urban residents to provide renewable materials for manufacturers. [ATL]	
	(3) Waste sorting improvement	Improve the quality of waste information; waste classification convenience; provide waste guidance; share accurate stories of waste and tips; flexible system design; public education on waste classification.	The smart bins *'Urbins'* created by KC can provide guidelines for people to recycle, effectively targeting those with low awareness of waste classification or low education level in developing countries. [KC]	https://www.thehindu.com/news/cities/chennai/kabadiwalla-connect-introduces-urbins-in-mylapore/article25335189.ece
Stimulate participation	(1) Attract user participation	Encourage poor communities to clean up plastic waste; help enterprises/governments/citizens to work together; meet essential components of consumer needs; create mutual trust between stakeholders; encourage interaction between individual links; significant benefits for waste pickers; positive public engagement; encourage emerging market consumers.	The rewarded tokens can attract users, residents participate in the recycling behaviour, recyclers can enhance the control of waste flow through the transparent recycling chain and local municipal departments can pay attention because they can obtain more accurate recycling data. RecycleGO's supply chain transport solutions are of interest to recyclers because they can optimise waste collection routes and reduce transport costs. [RecycleGO]	*The reward model we proposed would attract local recyclers, because it would improve their living conditions, especially in Haiti. (Manager of Plastic Bank [Indonesia])*
	(2) Entrepreneurial opportunities for recyclers	Mobilise recycling entrepreneurs; provide banking service for recycling enterprises; allow entrepreneurs to create local recycling business; allow to create local ownership model; provide business with valuable metrics.	The waste collection demands of Plastic Bank offered local recyclers opportunities to collect more waste and created recycling shops. [Plastic Bank] Empower provided similar recycling incentives to Plastic Bank but Empower built a local ownership model for local recyclers rather than control these shops. [Empower] KC created economic opportunities for informal waste aggregator sectors, better able to encourage them to collect waste from street pickers. [KC]	*The local collection points who reached out to us and it's like a local ownership model where you want them to on board using our system, anyone can establish their own local waste management business. (CEO of Empower)*

BCT benefits (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
	(3) Promote extensive cooperation	Cooperate with technology provider IBM; attract SC Johnson to join; involve NGOs on board; build connections between households; integrate informal sectors into recycling chain; connect residents, commercial, industries; get inspired by business partners; involve schools, municipalities.	Transparent closed-loop recycling chains can attract more stakeholders, such as retailers, and manufacturers from other industries. [All cases] Plastic Bank has opened eight branches with its main partner SC Johnson to expand waste collection, including mobile branches and scrap services. Also, Plastic Bank is in partnership with IBM, which offers blockchain underlying technology. [Plastic Bank] Blockchain offers opportunities to work with other organisations to develop new markets, design more interesting token services and expand the brand image of recycling companies or technology providers, which can attract more investment and even the attention of local departments. [Empower, RecycleGO, KC, ATL]	https://www.ibm.com/case-studies/plasticbank https://impakter.com/exploring-informal-waste-management-an-interview-with-siddharth-hande/
Social inclusion	(1) Monetising opportunities for informal sectors	Long-term benefits for financial inclusion for informal sectors; change financial aid ways; provide loans.	The tokenisation function of BCT can realise a more secure and cashless financial inclusion method and reduce the risk of cash robbery [Plastic Bank, Empower]. And, in the long run, it can contribute to financial inclusion, such as the provision of microfinance loans. [Empower]	*Because they do not have their own bank, if they can start using the e-wallet, they can maybe have access to financial services and even take our loans. (Legal Counsel of Empower)*
	(2) Equal working opportunities	Improve equal employment for waste pickers; stop the middleman intervention in recycling chain; everyone can get paid by recycling activities; gender quality by providing standard income.	In the process of blockchain-driven waste recycling, waste collectors including street waste pickers in the informal sector and local waste collectors can get equal employment opportunities of waste collection to earn money. [Plastic Bank, Empower, KC]	*Our recycling system rewards based on the weight of the collection, which means everyone follows the same exchange mechanism. (Manager of Plastic Bank [Indonesia])*
	(3) Humanitarian support	Offer income sources for street pickers; solve hunger and poverty; provide unskilled jobs; promote decent work; improve the lives of marginalised people; lifting communities out of poverty; charity donation; impact the individual or community through charitable donations; reward voucher for donating to charity.	The blockchain-based ecological recycling system integrates marginal recyclers such as waste collectors into the recycling chain and provides substantial and guaranteed recycling costs, which helps to improve the living conditions of waste collectors, especially in developing countries. [Plastic Bank, Empower, KC].	https://journals.openedition.org/factsreports/5143 https://solve.mit.edu/challenges/RethinkPlastics-en/solutions/17263

(Continues)

BCT benefits (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
			The broader engagement and more effective recycling programmes that result from BCT are able to recycle a greater amount of waste, with valuable recyclables being made available to charities. Part of the economic benefits of recycling can be donated to charitable organisations and this transparency model enables them to attract more donations. [Plastic Bank, ATL]	
Transparent recycling chains	(1) Trace recycling flows	Trace whole recycling process; fully transparent approach for plastic recycling; ensure visibility of recycling chain; redesign plastic value flows; track from production to consumption; high accessibility for stakeholder.	BCT provides visibility and transparency to the entire closed-loop recycling chain, where the process from waste collection to final remanufacturing is recorded, and no middlemen interfere with the process. [ALL]	*Our blockchain system has a high degree of security, and the data is presented to users in real time. (CEO of RecycleGO)*
	(2) Security of waste transactions	BCT ensures tokens security; provides safety data throughout recycling chains; digitalises token exchange traceability; encrypted codes cannot be tampered with.	BCT can record recycling information in a timely fashion, including the weight and variety of collection, which can help recyclers process and trade recyclables more efficiently. [ALL] BCT-based platforms can record users' recovery points and more securely protect digital currencies in exchange for subsequent physical rewards or public services. [Plastic Bank, Empower, KC, CryptoCycle, ATL]	https://solve.mit.edu/challenges/tiger-challenge-international/solutions/15541 https://solve.mit.edu/challenges/RethinkPlastics-en/solutions/17263
	(3) Advanced supply chain solutions	Track hauliers' dynamics, optimise waste collection routes; smart inventory optimisation.	Supply chain solutions based on BCT can help hauliers to pick up and transfer waste more efficiently, select the optimal route and help reduce idling time and no-load conditions of vehicles. [RecycleGO] BCT-based supply chain solutions can help recyclers more efficiently manage inventory, including tracking and counting. [RecycleGO]	*What we focused on in terms of our initial implementation of software was a logistics solution. We essentially built on Uber app, a waste management app. (CEO of RecycleGO)*
	(4) Stakeholder trust building	Connect stakeholders in trustable chain; affordable and comprehensive solution; share accurate story of waste; provide trust between public, producers and recyclers; building connections between households and Kabadiwallas; create trust data; transparency increases stakeholder trust.	Blockchain platforms can integrate the stakeholders of the entire closed-loop supply chain and, through the advantages of high transparency and traceability, can enhance the close connection and trust between every role of the supply chain. [ALL]	*We are proud of the fact that the system has built so much trust that even customers have direct access to the product's original information. (CEO of Empower)*

BCT benefits (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
Extended producer responsibility accountability	(1) Facilitate the implementation of EPR	Help private sector to follow extended producer responsibility; awareness of product history; constraining producer behaviour; response for extended producer responsibility; improve recycling culture.	The waste-tracking system provided by blockchain tracks the recovery process in a transparent and traceable manner, which requires recyclers and producers to more strictly comply with extended producer responsibility regulations. [Empower, ATL] KC integrates the informal waste ecosystem into the reverse logistics, enabling the municipal sector and recycling companies to pay more attention to the important role played by the informal sector in EPR. [KC]	https://www.cryptocycle.co.uk/what-is-reward4waste/ https://www.agoratechlab.com/single-post/2019/03/19/Agora-Tech-Lab-Mentioned-in-Sensa-Networks-Article https://www.planet.veolia.com/en/kabadiwalla-start-up-management-waste-urban-collection-india
	(2) Data analysis for municipal departments	Accurate recycling data for the government; complement the current infrastructure; share accurate story of waste; improve operation efficiency by data automation reporting.	The recycling transaction under BCT platform can record the data of waste recycling in real time, which is conducive to the supervision of municipal departments and the policy deployment of waste recycling. [ALL]	*Our platform is capable of recording waste data, which can be facilitated by the municipal authorities. (CEO of RecycleGO)*

APPENDIX C

THE IMPLEMENTATION BARRIERS OF BCT RECYCLING

Adoption barriers (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
Cognitive barriers	(1) Low recycling awareness	No awareness of garbage classification; indifference; lack of community recycling advocacy.	Many people still believe that recycling value is low with limited waste collectors or that it relies on informal sectors. [Plastic Bank, Empower, KC] The recycling awareness of ordinary users varies greatly between developing and developed countries. [ALL]	*One of the fundamental obstacles facing recycling is the mindset that waste has no value. (CEO of KC)*
	(2) Hesitates to deploy BCT	Not familiar with BCT; how it works; wait to see others; need more technical supports; no sufficient experience.	Blockchain requires the decision making from company's senior managers. However, the application of innovative technology in the recycling is still uncertain, including development costs and technical knowledge, which may cause managers to hesitate to use the new technology. [ALL]	*Blockchain technology is a relatively new concept, and while it interests many people, the majority is hesitant to adopt this new technology. (RecycleGO CEO)*
Technology barriers	(1) Lack of complementary infrastructure	Need IT teams; stakeholder cooperation; BCT platform building; software development; technical providers' support.	The deployment of blockchain requires sound infrastructure, including adequate upstream recycling systems, transparent and traceable recycling chains and effective planning by recyclers. Moreover, achieving full deployment depends on stable technology development. [ALL]	https://solve.mit.edu/challenges/tiger-challenge-international/solutions/15541
	(2) Difficulties in embedding existing systems	Integration of traditional recycling chain and technology; the risk of consolidation in the informal sector; recyclers do not know the technology.	The integration of innovative technologies and traditional recycling industries still needs to be explored, particularly the information asymmetry in the ecosystems of developing countries. [Plastic Bank, Empower, KC]	*Huge asymmetry of information means that a person who is looking to set up a processing plant has no information from which he can draw projections for his business. (CEO of KC)*
Internal barriers	(1) Lack of capital resources	Financial constraints; insufficient personnel; lack of technical personnel; additional requirements for the expansion of operations; need to work with technology providers.	The construction of a blockchain platform requires technical support, recycling companies need to buy technical services and technology providers also need capital to develop, such as iterative updates of application system. [ALL]	*We currently have limited funding, which limits our abilities for staff and operational expansion. (CEO of RecycleGO)*
	(2) Limited experience	Keep exploring; limited experience for reference; pioneers in the industry are limited.	The blockchain deployment of pioneer companies is mostly in the pilot stage, and full implementation requires long-term exploration, which lacks sufficient practical experience. [ALL]	*We are still in the exploratory stage, and there may be many uncertainties, such as the operation model in different regions may need to be adjusted. (CEO of Empower)*

Adoption barriers (themes)	Sub-themes	Underlying codes	Descriptions (case involved)	Example quotes (source)
External barriers	(1) Lack of governmental policies and intra-industry support	Expect government support; policy guidance is essential; the municipal sector has great influence; more environmental policies are needed; working with retailers; fierce competition in the recycling industry; manufacturers demand lower prices; the technology provider's solution does not match.	The deployment of blockchain as an innovative technology will bring disruptive changes to the recycling industry, which will require policy support from municipal departments. [ALL] Most of the recycling industry is still in the traditional recycling mode, while the new blockchain-driven recycling mode, despite its considerable benefits, is mainly piloted by pioneer companies and long-term benefits need to be explored. [ALL]	https://solve.mit.edu/challenges/RethinkPlastics-en/solutions/15640 https://solve.mit.edu/challenges/RethinkPlastics-en/solutions/17263
	(2) Attractive barriers	Users indicated that the recycling reward was not enough; the reward incentives are complex; token reward functions are not sufficient.	Attract for collectors: Blockchain platforms integrate circular chain stakeholders but need to attract more recycling participants to collect recyclables, which is particularly important in developed countries where there is a lack of informal sector recyclers' contributions. [RecycleGO, CryptoCycle, ATL] Attract end users: After the completion of the blockchain platform and application building, how to attract more end user participation is also critical, which will require more attractive incentive mechanisms. [Plastic Bank, Empower, KC, CryptoCycle, ATL]	*We still need to update the reward model to attract more users to participate, which needs further exploration. (Legal Counsel of Empower)*
	(3) BCT legislative barrier	Conditions for converting digital currency to local currency; there are still legal defects; waiting for the law to be updated; risk of being banned; illegal behaviour.	The token service of the blockchain platform involves cryptocurrency, but there is no perfect legislation on the commercial development of blockchain, which may have legal loopholes (such as money laundering). [ALL]	*We are well aware however that states are increasingly concerned by the different uses one can make of cryptocurrencies, digital tokens and blockchain, and we are worried about the use of blockchain for illegal activities.* https://solve.mit.edu/challenges/tiger-challenge-international/solutions/15541