Unlocking a Circular Economy with Blockchain: Recommendations for Policymakers and Researchers

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SUMMARY

Blockchain technology can revolutionise the circular economy in Hungary and Europe by promoting resource efficiency. This paper analyses the current regulatory environment and sectoral results to identify areas for improvement to foster blockchain adoption. We propose well-structured recommendations for a secure legal framework, business incentives, and data-driven waste management practices, all informed by legal and scientific document analysis. We identify research gaps related to each recommendation, aiding researchers in prioritising areas for further scientific investigation.
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INTRODUCTION AND RESEARCH QUESTIONS

Environmental changes are not isolated events but interconnected changes in complex systems, a fact that underscores the complexity of the issues we face. The steady increase in greenhouse gas emissions and the climate crisis generate socio-legal and economic issues. Examples of social impacts are migration, mass starvation, water crises, conflict, and poverty. Legal consequences include the tightening of environmental laws, the creation of new legislation and court decisions. Economic impacts include crop losses, damage, increased costs and job losses. Environmental change triggers a whole series of complex social relations. For example, changes in agricultural structures lead to changes in agricultural production, labour markets and consumer behaviour. These changes are closely interlinked and can have consequences that are difficult to predict. Is there a chance of halting or at least reducing these processes by highlighting a key element? The answer needs to be clarified, and different experts have different views. Some argue that the only way to tackle the climate crisis is to simultaneously tackle all the areas concerned. Others believe we must identify the most important key elements and focus interventions on these.

Here, we propose blockchain technology as a vital tool for developing the circular economy. Blockchain, a distributed ledger technology (DLT), enables the secure and transparent distribution of values and information without a central intermediary. It establishes a peer-to-peer (P2P) network among geographically dispersed or untrusting parties, facilitating direct, decentralised transactions (Juhász, 2020a). Blockchain can bring many benefits to the circular economy, including decentralisation, transparency, security, and efficiency. Blockchain technology offers several concrete applications in the circular economy (Joshi et al., 2023). These include benefit tracking, lending and sales, and quality assurance, among many other applications.

However, an interesting question, and a source of danger, is how long the trust between the parties will be maintained. While our paper will primarily focus on the link with the circular economy, it is necessary to refer to some issues that may be relevant even for blockchains in the circular economy—for example, ethical concerns about the application of the technology. Blockchain technology has been significant in the grey economy for a long time. Many people prefer its decentralised nature. However, can this feature be maintained in a fully legal, formalised, and somewhat centralised framework? Alongside this, technological interdependence is a significant issue. This is particularly evident in the use of cryptocurrencies. The legalisation of Bitcoin creates a new situation, but it leaves open many issues not secured by the legal framework and that are raised for the time being in the form of ethical concerns.

In this paper, we briefly describe the applications and the potential benefits and then suggest possible directions for the necessary regulatory action. An overview of the circular economy's theoretical foundations is necessary to understand the subject. This is the subject of the next section.

CIRCULAR ECONOMY: THEORETICAL APPROACHES AND POTENTIAL BENEFITS

The circular economy is an economic system that reduces waste and pollution by reusing and recycling natural resources and materials (Olajos, 2016). In contrast to the traditional linear economy, in which products' production, use and waste move in one direction, the circular economy preserves the value of products, materials and other resources for as long as possible. The circular economy aims to minimise waste production and emissions of harmful substances, optimise the use of resources in production and consumption processes, and preserve the value of products, materials and other resources (Bułkowska et al., 2023). The circular economy has many environmental, economic and social benefits. The circular economy is the economy of the future, offering opportunities to reduce environmental pressures and create a more sustainable future. In developing circular economy systems, we aim to minimise waste generation and emissions of harmful substances throughout the life cycle, including implementing a waste hierarchy (EU Directive 2020/852).

The concept of a circular economy is now widely accepted by researchers and practitioners, but there has been disagreement on its interpretation. Accordingly, several definitions of the circular economy are presented below, comparing the approaches and emphases of the international organisations that have defined the topic. The Ellen MacArthur Foundation's definition emphasises the importance of eliminating waste and pollution in production systems as a primary task of the circular economy. As part of this, it reinforces the objective of keeping products and materials in use for as long as possible. The Foundation also addresses the concept of regeneration of natural systems as a priority area of the circular economy. The World Economic Forum definition emphasises the intention and plan to create a restorative or regenerative industrial system. Accordingly, it calls for eliminating waste through the excellent design of materials, products and production systems. The World Economic Forum attaches great importance to a shift to renewable energy sources and eliminating toxic chemicals. According to the European Commission, the circular economy is an economic framework that encourages resources to be used for as long as possible. It also emphasises extracting the maximum value from resources while they are in use. As a key objective, the Commission promotes the recovery and recycling of products and their raw materials at the end of their (earlier) life. The United Nations Industrial Development Organisation (UNIDO) stresses the need to develop restorative or regenerative industrial systems and the related design intentions. It aims to ensure that products, components and materials retain their usefulness and value for as long as possible.

Looking at the different concepts, it can be said that although all definitions agree on the principles of value preservation, waste minimisation and the promotion of resource efficiency, each source gives a slightly different emphasis or perspective to the concept of a circular economy. The Ellen MacArthur Foundation, for example, emphasises the design aspect (Ellen MacArthur Foundation, n.d.), while the World Economic Forum stresses intention and planning (World Economic Forum, 2022). The European Commission attaches great importance to the longevity and utilisation of resources (European Commission, 2023), and UNIDO emphasises the preservation of utility and value (Müller, 2023). All these approaches emphasise the holistic and sustainable nature of the circular economy.

The concept of the circular economy is also discussed in different ways in academic works. Kirchherr et al. (2017) identify about 114 definitions of the topic and distinguish three main approaches:

- Materials management approach: This approach defines the circular economy as the recycling or reusing of materials and energy to the greatest extent possible;
- Environmental approach: This approach describes the circular economy as an economic system that reduces environmental pressures;
- Systems Approach: This approach describes the circular economy as an economic development where growth is coupled with reduced environmental pressures.

The comparative theoretical work of Kirchherr et al. also confirms that the definition of the circular economy today is diverse and encompasses several ideas. Significant overlaps exist between the different basic concepts and the differentiable approaches that have emerged. Overall, it can be concluded that most primary schools of thought on the circular economy have a specific approach, but the concepts are not distinguishable (Németh, 2021).

The potential benefits of the circular economy have yet to be fully explored from an academic perspective. However, the evidence suggests that the circular economy can significantly contribute to environmental, economic and social sustainability (Upadhyay et al., 2021).

The circular economy can have several benefits, including the following:

1. Reducing the demand for raw materials. In a circular economy, materials and energy are reused repeatedly, reducing the demand for raw materials. This reduces environmental pressures and can contribute to sustainable development.
2. Long-lasting use of value-added products, eliminating waste. In a circular economy, products are designed to be durable and easy to repair or recycle. This reduces waste and increases the rate of material reuse.
3. Creating new markets and new products, adding value. The circular economy also encourages the creation of new markets and new products. This can create new business opportunities and contribute to economic growth.
4. Security of supply and reduction of greenhouse gas emissions. The circular economy can contribute to the security of supply and reduce the growth of greenhouse gases.
5. Creating new jobs. The circular economy can create new jobs in the engineering and maintenance of green systems, in the operation of recycling systems and many elements of the value chains of the bio-based economy.
6. Innovation and entrepreneurship. The circular economy encourages innovation in technical and economic design, recycling and reuse, the development of an economy based on "bio" solutions, and promoting entrepreneurship, often in rural, small-scale structures.

The circular economy has several benefits, including reducing environmental pressures, fostering sustainable economic growth, creating new jobs, and stimulating innovation.

CHALLENGES AND ACTION PLANS FOR DEVELOPING THE CIRCULAR ECONOMY

A circular economy is an ambitious goal essential to achieving sustainable development. However, it is also a fact that there are still many challenges to overcome to achieve a circular economy. The circular economy requires several technological innovations that are not yet available, and their integration into a profit-oriented economic system is complex. Furthermore, the difficulty of changing consumer attitudes is also significant. Several open social science dilemmas need to be adequately addressed if the successful adaptation of circular economy models is to contribute to reducing environmental pressures and making economic growth sustainable. The main problems and needs for action arise in the following areas (Németh, 2021):

- Transforming the waste management system: The current waste management system focuses on the disposal of waste rather than its recycling. To achieve a circular economy, the waste management system needs to be transformed to focus on recycling and reuse of waste.
- Innovation in product design: To achieve a circular economy, product design and consumer behaviour must change. Products must be designed to be more recyclable and reusable.
- Changing consumer behaviour: Consumers must be encouraged to use products for longer and recycle or reuse them when they are no longer needed.

To achieve a circular economy, the European Commission adopted an action plan focusing on seven key areas (European Parliament, 2023). The Commission's action plan is essential to achieving a circular economy. The measures set out in the plan can contribute to reducing environmental pressures, making economic growth sustainable and promoting social justice (European Parliament, 2021a). The envisaged directions of development are as follows:

- Product design and manufacture: The Action Plan prioritizes the design and manufacture of products with enhanced durability, repairability, and recyclability. The Commission has implemented measures, such as [PR1] legislation, to extend product lifespans and promote repair and recycling practices.
- Raw materials: The Action Plan fosters a reduction in raw material use and promotes the utilization of recycled materials.

This objective is pursued through measures including enhancing raw material recovery and recycling and encouraging research and innovation to facilitate a transition towards a circular economy.

- Waste management: Waste minimization and enhanced management: The Action Plan prioritizes the reduction of waste generation alongside improvements in waste management efficiency. This is achieved through measures including the reinforcement of the waste hierarchy principles and the optimization of waste management systems.
- Infrastructure: The Action Plan fosters the development of infrastructure crucial for a circular economy transition. This is achieved through measures such as expanding waste collection and processing capabilities and creating financial instruments to support this transformation.
- Education and awareness: The Action Plan prioritizes fostering awareness and knowledge of the circular economy. This objective is pursued through measures including the support of educational programs on circular economy principles and the implementation of campaigns to advocate for the transition towards a circular economy.
- Community involvement: The Action Plan fosters a shared ownership model, encouraging collaboration between citizens and businesses to facilitate the transition towards a circular economy. This is achieved through measures including supporting community-driven initiatives and promoting business practices that contribute to the transition.

The circular economy is vital at the ideological and lower levels of regulation. In the New Circular Economy Action Plan, the European Parliament precisely sets out the tasks needed for the administrative transition. It is necessary to see that the new economic concepts do not work under the old administrative system. Therefore, The European Parliament has called on the Commission to identify the regulatory measures and other actions needed to remove the administrative and legal obstacles to the circular economy based on sharing and services and stimulate its development (European Parliament, 2021b).

However, the uptake and promotion of services based on sharing depends on the legislator and the attitude of individuals and society. The individual's attitude to the sharing economy requires a new approach that overrides the individual ownership systems of the past. Digital communications and growing trust in digital technologies have allowed decentralised peer-to-peer networks to flourish. This is what enables the sharing of goods and services between individual users. The result of this new approach and drive for economic efficiency is that consumers can borrow, exchange and share goods and services through different platforms (mainly online) on an unprecedented scale. These platforms offer a chance to fundamentally reorganise society by integrating sharing into the structure of the economy, which could lead to a global social shift away from capitalism towards post-ownership (Del Vecchio, n.d.). This could even help to integrate individuals into the circular economy. However, the right incentives are required, even if only for firms and enterprises. As we can see, blockchain technology is a good tool for effectively implementing the circular economy (Brown, 2022).

THE POTENTIAL OF BLOCKCHAIN TECHNOLOGY TO PROMOTE THE CIRCULAR ECONOMY

Blockchain technology has several potential benefits for promoting sustainable consumption and production. Cryptocurrencies can provide financial support for projects promising sustainable goods and services, finance sustainable energy sources, or purchase goods and services linked to environmental goals. Another significant new opportunity is tracking products throughout their life cycle and facilitating recycling. Data stored on blockchain technology is easily accessible and verifiable. This will allow consumers to quickly know where a product was made, what it is made of, what stages it has passed through and how it can be recycled or reused (Mohamed et al., 2023). The technology can ultimately track products throughout their life cycle (!). This can help consumers make more informed choices about what they buy and allow the producer to be contacted directly (with questions, subsidies, etc.).

It is, therefore, important that the categories of contract law are linked to this. Innovative contract solutions are coming to the fore. One form of this is the blockchain contract. These contracts must be type-independent and self-executing. They are able –mainly when supported by the use of artificial intelligence – to provide contractual guarantees that enforce and facilitate the performance of the contract between the two parties without the need for a face-to-face meeting of the parties. The contract is often the program, the code (Juhász, 2020b). Blockchain contracts can do more than a classic contract; they can symbolise the green transition by being paperless. Blockchain contracts are already the domain of partners using globalised stable info-communications and telecommunications networks (Ayan et al., 2022). This is a new form of contractual trust in today's globalised world. Parties do not meet the quid pro quo when they exchange virtual money and

cryptocurrency e for some service or product. Because of these characteristics, blockchain contracts are well suited to contractually managing processes that can help achieve a global circular economy.

Blockchain allows the production and consumption of green energy sources such as solar panels or wind power to be tracked. It can also help to finance projects to combat climate change, where the distributed and transparent management of funds can facilitate the efficient use of aid. The combination of blockchain and IoT (the Internet of Things) can enable secure and decentralised data exchange between devices, which can be helpful in various applications. For example, green smart devices can help manage energy more efficiently and create a more sustainable lifestyle (Munir et al., 2022). Blockchain can help track green financial products and services and manage sustainable investments. Its decentralised and transparent nature can help reduce environmental risks. It will also enable transparency in global supply chains, especially in the food and clothing industries. This will help identify and prevent pollution, exploitation and other environmental problems. The technology can also be used to improve the efficiency of recycling systems. For example, blockchain can be used by waste collection companies to track recycled materials (Sahoo et al., 2022). This can help companies manage waste more efficiently and reduce pollution. There are many other applications in the field of waste management. Among other things, the technology allows waste to be tracked throughout its life cycle, which helps monitor its origin and composition and improves recycling efficiency. The technology can be used to organise decentralised markets for the sale of waste, which will help encourage waste recycling by creating an economic incentive for waste holders. Cryptocurrencies can also be used directly to encourage and reward recycling. In blockchain-based systems, consumers can be rewarded with cryptocurrencies for returning or recycling waste products, leading to more efficient and responsible consumer and citizen choices. A few academic studies have already strengthened the argument by demonstrating the broader applicability of blockchain for sustainability goals (Mulligan et al., 2024).

CARBON CREDIT SCHEMES AND THEIR DEVELOPMENT POTENTIAL

The EU Green Deal is the EU's new growth strategy to achieve climate neutrality by 2050. The objectives of the Green Deal include increasing resource efficiency, improving competitiveness and creating a just society (Jakab, 2022). Hungarian Government Decree 320/2003 (17. VII) regulating the Hungarian Emissions Trading System can also contribute to achieving the Green Deal objectives. The Regulation allows companies to use EU allowances to reduce their emissions, to reduce emissions from other companies and for trading purposes. Regarding the functioning of the allowance system, it is worth noting that EU Allowances (EUAs) are a vital instrument of the EU Emissions Trading System (ETS). EUAs are rights that allow their holders to emit a certain amount of greenhouse gases. ETSs aim to reduce greenhouse gas emissions by limiting emissions to a limited number of allowances. Meanwhile, the Fair Transition Mechanism (MA) seeks to guarantee a fair implementation of the European Green Deal. Through the MA, the EU can help to ensure that the fight against climate change does not overburden certain groups in society and that everyone has the opportunity for sustainable development.

The use of EUAs in the Hungarian energy industry is still in the early stages. Operators use EUAs primarily to reduce their emissions, but there is also growing interest in the commercial use of EUAs. The Hungarian ETS is regulated by Government Decree 320/2003 (17. VII). According to the regulation, EUAs can be used to reduce their emissions, reduce emissions from other operators, and for commercial purposes. The regulation has the unconcealed aim of significantly taxing the country's largest carbon emitters (Clamba, 2023). Installations with significant carbon dioxide emitting activities covered by the ETS have a fixed number of allowances per year, which entitle them to emit a certain amount of CO_2 "for free"— however, the Hungarian rules in their current form run counter to the principles of carbon credit systems. Moreover, by enforcing high taxes, the state is causing an unjustified disadvantage to the biggest emitters of the raw materials needed to make the economy work, such as cement or fertiliser.

The Commission believes that carbon credit schemes complement other measures to support the transition to a circular economy. Carbon credit schemes should be combined with other measures, such as extending the life of products, encouraging repair and recycling and reducing waste. The Commission also highlights the potential of blockchain technology. It mainly welcomes the fact that blockchain technology can provide new tools for the transition to a circular economy, as it can be used to trace and control the path of products and materials from production to use and waste. They say this can help reduce waste, encourage reuse and product improvements, and promote sustainable business practices. The Commission plans to support research and development of blockchain technologies, including applications for carbon credit schemes. The development of a regulatory framework for using blockchain technology is envisaged, followed by support for businesses using the technology. Building upon the need for improvement in Cap-and-Trade programmes, the Commission recognises the potential of carbon credit schemes as a tool for a circular economy. (European Commission, n.d.)

One of the significant elements of the Commission's plan for utilizing blockchain for sustainability purposes is a functioning Cap-and-Trade (CAT) system. According to scholars, while cap-and-trade programs are prevalent for emission reduction, they face challenges in establishing a stable international market due to regional regulations. Blockchain technology, a decentralized and secure system, offers a potential alternative platform for CAT implementation. Its features, including peer-to-peer transactions, enhanced privacy, and smart contracts, could address current shortcomings and encourage broader participation in carbon credit trading. (Mankar, 2022).

Despite blockchain's potential to transform the circular economy across various sectors, significant work is still needed to bridge the gap between theory and real-world applications. To illustrate this point, we will explore a few specific use cases and challenges associated with blockchain implementation in different sectors. These examples serve as a starting point for understanding the broader challenges. Subsequently, drawing on these practical considerations, we will propose a well-structured policy and research recommendation agenda specifically tailored for policymakers and researchers.

Sectoral Examples of Blockchain-Based Green Innovations

According to Woo et al. (2021), blockchain technology can address some of the construction sector's challenges in reducing its carbon footprint. Traditional methods for measuring, reporting, and verifying (MRV) energy use and emissions are insecure and complex, hindering participation in carbon credit markets. Existing building energy performance (BEP) audit schemes lack a robust structure for accurate carbon MRV. The authors propose that blockchain technology can be harnessed to create a digital BEP MRV system for the building sector, facilitating participation in established blockchain carbon credit markets. Other applications like household and transportation carbon offset projects linked to renewable energy trading are also being explored. However, research suggests that forestry and renewable energy projects might be better suited for blockchain due to stricter quality criteria for carbon offsets (Vilkov & Tian, 2023).

Carbon credits also hold great opportunities. Zhang et al. (2023) suggest that blockchain technology has the potential to significantly enhance carbon trading efficiency and effectiveness in China's electric power sector. The article acknowledges the rapid development of blockchain technology but highlights the critical need for a synchronised legal and regulatory framework. This includes establishing laws, management regulations, and policy documents to govern the industry. Addressing critical issues like modifications to smart contracts and reputation mechanisms within these documents is essential. The study states that considering the potential applications of blockchain beyond carbon trading (e.g., finance and healthcare), the government should develop a unified and standard legal system.

The further development and deployment of blockchain technology can reduce waste and pollution and more efficiently use resources by enabling actors to store data and access previously unavailable information securely and transparently. Best practices; an excellent example of this is the venture called Social Plastic, whereby poor people in third-world countries can collect rubbish from the beach, the ocean or the coast and bring it to a Plastic Bank to receive tokens that can be exchanged for products or services, such as minutes on their phone. Moreover, Henkel produces recycled packaging from the collected waste and markets its products in Europe in this packaging (Mélypataki, 2022).

Analysing waste management data practices, Jiang et al. (2023) write about the challenges and possible solutions. Despite the exciting potential of blockchain technology and its associated potential, like smart contracts and distributed ledgers for waste management, significant challenges remain regarding data acquisition and transparency. Even with advanced data traceability technologies, current IoT and blockchain solutions struggle to capture all relevant product data throughout the product's entire lifecycle. The lack of robust audit functions increases the risk of electronic waste (E-waste) entering unregulated markets. This can lead to environmental hazards or security breaches, as sensitive data or radioactive materials might be stolen from improperly disposed devices. The authors explore potential solutions to address these challenges and improve data acquisition and transparency in waste management. Research is ongoing to develop new technologies like decentralised data-sharing frameworks for the Industrial Internet of Things (IIoT) that prioritise data security, efficiency and reliability for massive data management. One approach involves encrypting data and storing it on IIoT platforms when registering new products. Examples include blockchain-based IoT data marketplaces and decentralised data trading platforms. Beyond technological advancements, fostering data sharing among government agencies through policy interventions can enhance transparency and hold stakeholders accountable.

Vilkov and Tian (2023) propose blockchain technology as a core element for a new model in carbon markets, aligning with the "3D's concept" of decentralisation, decarbonisation, and digitalisation, which is also our crucial concept here. The critical point is that blockchain can potentially improve the current system by combining national registries and non-state actor contributions through tokenisation, facilitating

long-term climate goals. However, the implementation requires careful consideration of potential drawbacks alongside benefits, as explored in a previous study by the authors.

According to Baralla et al. (2023), while a significant portion of research explores the potential of blockchain for waste management, many studies lack concrete technical details regarding the implementation or specific platforms utilised. This highlights a need for practical recommendations tailored to the existing waste management infrastructures. Furthermore, effective policy frameworks will be crucial for incentivising adoption and ensuring the responsible use of blockchain technology within the waste sector. Building upon applying blockchain to various stages within the waste lifecycle, we can explore its potential for various sectors. For instance, according to Baralla et al. (2023), some studies track waste across the entire chain, aligning with a circular economy approach. Others target stages like waste generation and collection, potentially promoting citizen engagement. By focusing on practical applications in Hungary and the EU in developing supportive policy frameworks, we can identify the most suitable stages for integrating blockchain technology within the existing waste management system, ultimately fostering a more sustainable and efficient circular economy. There are a number of practical solutions that the regulation can foster. Steenmans et al. (2021), for example, write about the possibilities in Extended Producer Responsibility and Right to Repair policies. The following section gives a structured picture of proposed general and specific policies to better current legislative agendas.

BUILDING A SUPPORTIVE ECOSYSTEM

Having explored blockchain technology's scientific background and potential for the circular economy, we now turn to practical legal and scientific considerations. This section outlines well-structured policy recommendations to foster blockchain's responsible and effective adoption in Hungary and Europe. We explore and structure policy and scientific research agenda recommendations and identify research needs to bridge the gap between the potential of blockchain and its practical implementation. These recommendations are informed by a comprehensive legal and scientific documents analysis, ensuring they address key challenges and leverage existing knowledge. Our recommendations are structured for three crucial pillars:

I. Building a stable and secure environment for blockchain applications is essential. This pillar proposes recommendations for fostering a legal system that supports innovation while mitigating risks.
II. Encouraging business adoption is vital for the widespread use of blockchain in the circular economy. For the second pillar, we propose practical measures to incentivise businesses to integrate blockchain technology.
III. Blockchain offers unique capabilities for transforming waste management practices, a key area of circular economy practices. The third pillar identifies key concepts for implementing data-driven waste management solutions.

I. General Regulatory Policies

Based on current literature, our findings suggest that establishing a unified and standard legal system across different sectors can significantly accelerate the adoption of blockchain technology (see Table 1). This would create a stable and predictable business environment, fostering innovation and investment. However, harmonising legal frameworks across jurisdictions can be complex and time-consuming. Additionally, a one-size-fits-all approach may limit flexibility in addressing the specific needs of different blockchain technology sectors. Further research is needed to explore how to balance harmonisation and flexibility in legal frameworks. Pilot programmes conducted across various industries and jurisdictions can inform the development of a unified legal system that promotes innovation while addressing sector-specific concerns.

Implementing a robust data security and governance framework is crucial for ensuring secure and reliable data management within blockchain systems. This fosters trust in the technology by protecting user privacy and data integrity, ultimately leading to more reliable decision-making based on accurate data. Developing and maintaining a comprehensive data governance framework can be an ongoing challenge, requiring consistent monitoring and adaptation to keep pace with technological advancements. Implementing robust security measures may also increase operational costs for businesses utilising blockchain technology. Further research is needed to develop industry-specific data governance standards tailored to the unique needs of different blockchain applications. Further research should explore cost-effective security solutions and data storage technologies that optimise user privacy and data integrity while remaining financially viable for businesses.

Table 1

General Regulatory Policies for Blockchain Adaptation

Policy Recommendation	Strengths	Weaknesses	Practical methods for governmental implementation
1. Unified and Standard Legal System	- Promotes wider adoption and innovation - Creates a stable environment for businesses	- Requires harmonisation across jurisdictions - May limit flexibility in addressing sector-specific needs	- Engage in international cooperation to develop a unified legal framework. - Conduct pilot programmes in different sectors to inform future legal considerations.
2. Data Security and Governance Framework	- Ensures secure and reliable data management - Promotes data privacy and user trust - Improves data quality and integrity for decision-making	- Requires ongoing monitoring and adaptation - May increase operational costs for businesses	- Develop industry-specific data governance standards for blockchain applications. - Invest in secure data storage and access control technologies. - Conduct regular data audits and quality checks.
3. Cost-effectiveness Measures	- Creates a level playing field for businesses - Encourages adoption through incentives	- May create initial compliance costs	- Develop clear guidelines and standards for data protection with blockchain. - Phase in regulations to allow for industry adaptation. - Conduct cost-benefit analyses of different incentive options.

Source: own editing

Economic theory suggests that well-designed regulations and incentives can influence business behaviour. Cost-effectiveness measures aim to create a level playing field by minimising compliance costs for businesses entering the blockchain landscape. Incentive programmes can encourage firms to invest in and integrate blockchain solutions into their operations. Further research is needed to identify the most effective and targeted incentive structures for promoting blockchain adoption. Cost-benefit analyses should be conducted to evaluate the long-term economic benefits of blockchain implementation compared to the initial compliance and operational costs.

II. General Implementation Measures

The successful implementation of any technology hinges on a skilled workforce. Investment in talent development for blockchain technology builds upon existing knowledge in computer science, cryptography, and distributed systems. By creating educational and training programmes, policymakers can address the talent gap and ensure a workforce equipped to handle the complexities of blockchain systems (see Table 2).

Further research is necessary to develop practical models for addressing the talent gap in the blockchain industry. This could involve studying the impact of different educational and training programmes on creating a skilled workforce. New scientific results are crucial to identifying optimal strategies for balancing harmonisation and flexibility in legal frameworks. This could involve a comparative analysis of existing blockchain regulations across jurisdictions and exploring models for flexible legal frameworks that adapt to sector-specific needs. Pilot programmes serve as valuable research tools. Data collected from these programmes across different sectors and locations can inform the development of a unified legal system that promotes innovation while addressing sector-specific considerations.

Table 2

General Implementation Measures for Blockchain Adaptation

Policy Recommendation	Strengths	Weaknesses	Practical methods for governmental implementation
4. Talent Investment	- Addresses the talent gap - Creates a skilled workforce	- Requires investment in education and training programmes - It may take time to see a return on investment	- Partner with educational institutions to develop blockchain-focused curricula. - Offer scholarships and training programmes for blockchain professionals. - Foster international collaboration and knowledge exchange.
5. Business Incentives	- Encourages adoption through incentives - Makes blockchain technology attractive for businesses	- May be difficult to target effectively	- Develop clear guidelines and criteria for awarding incentives. - Conduct cost-benefit analyses of different incentive options. - Monitor the effectiveness of incentive programmes and make adjustments as needed.
6. Public Authority Staff Training	- Improves capacity for blockchain implementation and oversight	- May require significant resources	- Develop training programmes tailored to the specific needs of public authorities. - Partner with universities and industry experts to deliver training programmes. - Provide ongoing professional development opportunities for public authority staff.
7. Pilot Programmes	- Accelerate learning and adoption - Identify and promote best practices	- May not apply to all regions or sectors - Require careful selection of participants	- Conduct feasibility studies to identify suitable locations and participants for pilot programmes. - Collaborate with leading cities and businesses to develop innovative solutions. - Continuously monitor and evaluate the results.

Source: own editing

Incentive programmes are a well-established policy tool encouraging businesses to adopt new technologies. In blockchain, incentives aim to overcome initial investment hurdles and encourage experimentation. Policymakers can draw on economic theory on technology adoption and diffusion to design incentive programmes that are targeted and effective in promoting blockchain use cases across different sectors. Further research should inform the development of effective and targeted business incentive programmes. This could involve studies that evaluate the effectiveness of various incentive structures (e.g., tax breaks and subsidies) in promoting blockchain adoption in specific sectors.

Effective governance of blockchain technology requires public authorities to understand its potential and limitations. Training programmes for public authority staff leverage existing knowledge of regulatory frameworks, emerging technologies, and public policy to equip them with the skills necessary to oversee the responsible implementation of blockchain technology. More research is needed to develop cost-effective training programmes for public authorities overseeing blockchain implementation. Analysing the specific needs of public authorities can guide the development of targeted training programmes.

Pilot programmes serve as a scientific method for testing the feasibility and effectiveness of new technologies in real-world settings. By implementing blockchain solutions in controlled environments, policymakers can gather data on technical performance, user behaviour, and potential challenges. This data can then inform the development of regulations, incentive programs, and best practices for large-scale blockchain adoption since pilot programmes offer valuable data for future blockchain implementation strategies. Research should explore practical methods for designing and evaluating pilot programmes to ensure they generate meaningful data.

III. Special measures for circular economy adaptation

Circular economy principles aim to minimise waste and maximise resource recovery through product life cycle extension. Blockchain can create immutable records of material composition, ownership, and location (see Table 3). Transparency allows businesses to optimise resource utilisation, identify opportunities for reuse and recycling, and ultimately reduce waste generation. Governments should encourage the development of standardised data formats for material tracking on blockchains by funding research initiatives and convening industry working groups. Pilot programmes integrating blockchain with existing waste management infrastructure can also be implemented to assess feasibility and identify cost-effective solutions. Further research is required to develop standardised data formats for material tracking within blockchain systems. Such standardisation would ensure interoperability across different platforms and facilitate seamless information exchange within the circular economy. Traditional waste management systems often lack transparency, hindering efforts to improve recycling and reuse rates. Blockchain technology can integrate seamlessly with existing waste management infrastructure by providing a secure and transparent platform for tracking waste streams. Smart contracts could automate waste sorting and incentivise responsible disposal practices. Real-time data on waste composition and location would enable optimised collection routes and improved resource allocation within the waste management system. Policymakers can incentivise waste management companies to adopt blockchain technology by offering grants or tax breaks for successful integration projects. Funding research collaborations between waste management companies, technology developers, and social scientists can also address the blockchain implementation's potential social and economic impacts. Research is crucial for developing secure and scalable solutions for integrating blockchain with waste management databases and tracking systems. Additionally, research is needed to explore the potential social and economic impacts of blockchain-enabled waste management, such as job displacement within the waste management sector and the potential for social equity concerns.

Facilitated by blockchain technology, decentralised waste markets could revolutionise waste management by creating a transparent and efficient platform for waste exchange. Waste generators could list their waste streams, specifying material composition and location. Potential recyclers or remanufacturers could bid on these waste streams, creating economic incentives for waste diversion from landfills. Smart contracts could automate transactions and ensure secure payment upon delivery of the waste material. Governments can play a role in facilitating the development of a decentralised waste market by funding research into secure trading platforms and dispute resolution mechanisms. Additionally, regulatory frameworks can be established to ensure transparency and fair competition within the decentralised marketplace.

Significant research is needed to develop robust and secure trading platforms for waste exchange within a decentralised market. This research would involve exploring consensus mechanisms suitable for waste transactions, designing secure, intelligent contracts for waste ownership transfer, and establishing mechanisms for dispute resolution within the decentralised marketplace. Public databases built on blockchain technology can promote responsible waste management practices and deter illegal activities. By recording waste collection, transportation, and disposal data on an immutable ledger, blockchain can increase transparency and accountability within the waste management sector. Public access to this data would empower citizens to hold waste management companies accountable for their practices and encourage responsible disposal behaviours. Policymakers can mandate public databases built on blockchain technology for waste management data. Additionally, they can develop and enforce data governance frameworks that ensure transparency, accountability and data privacy within these public databases.

Investing in user-friendly data visualisation tools can empower the public to hold waste management companies accountable. Research is needed to develop clear data governance frameworks for public waste management databases. This includes establishing data ownership rights, access control mechanisms, and data privacy protocols to ensure the responsible management of sensitive information within the public database. Additionally, research is needed to explore effective data visualisation and dissemination methods to ensure accessibility and user-friendliness for the public.

Table 3

Special measures for circular economy adaptation

Policy Recommendation	Strengths	Weaknesses	Practical methods for governmental implementation
8. Encouraging Circular Economy Applications	- Promotes waste reduction, reuse, and recycling	- Requires infrastructure development for tracking materials	- Invest in research and development of blockchain solutions for the circular economy. - Partner with waste management companies for pilot programmes. - Develop clear ownership and responsibility models for material data.
9. Waste Management Integration	- Increases transparency in waste management - Improves recycling and reuse	- May disrupt existing waste management practices	- Partner with waste management companies for pilot programmes. - Develop training programmes for waste management personnel on blockchain technology. - Provide financial and technical assistance to waste management companies adopting blockchain technology.
10. Decentralised Waste Market	- Creates economic incentives for sustainable practices	- Requires development of a robust and secure trading platform	- Conduct feasibility studies to assess the potential of a decentralised waste market. - Develop clear rules and regulations for operating a decentralised waste market. - Pilot-test the decentralised waste market concept in a controlled environment.
11. Public Database for Waste Management Transparency	- Promotes responsible waste management practices - Reduces illegal activities	- Requires investment in data collection and management infrastructure	- Develop clear guidelines and standards for data collection and reporting. - Partner with waste management companies and local authorities to collect data. - Implement strong data security measures to protect sensitive information.

Source: own editing

CONCLUSION

This analysis explored policy recommendations for fostering the responsible and secure adoption of blockchain technology, focusing on three categories: general regulatory policies, general implementation measures, and special measures for circular economy adaptation. Unified legal systems and robust data governance frameworks are crucial for creating a stable and secure environment for blockchain applications. Cost-effectiveness measures like targeted incentives can encourage business adoption. Investing in talent development, training public authorities and conducting pilot programmes equip stakeholders with the necessary skills and knowledge. The focus then shifted to integrating blockchain with the circular economy. Standardised data formats and cost-effective infrastructure are essential for tracking materials within the supply chain. Integrating blockchain with existing waste management systems can improve transparency and resource allocation. Decentralised waste markets facilitated by blockchain offer economic incentives for waste diversion. Finally, public databases built on blockchain can promote responsible waste management practices and deter illegal activities. By addressing these considerations and supporting further research, policymakers can unlock the potential of blockchain technology for a more efficient, transparent and sustainable future.

The most effective approach might be a combination of baseline regulations and industry-specific guidelines. The former is a core set of rules that apply to all blockchain applications, regardless of industry. These would address fundamental issues like data security, consumer protection and anti-money laundering. The latter specifies additional guidelines or best practices to address different industries' risks and needs. These guidelines could be developed through collaboration between governments, industry experts and researchers.

Given the technology's scope and novelty, researchers are critical in guiding its responsible implementation. Their work on developing standardised

data formats, secure trading platforms for waste exchange, and effective data governance frameworks is essential for overcoming technical challenges and ensuring transparency within the system. Additionally, research into blockchain's social and economic impacts on waste management practices is crucial for mitigating potential disruptions and promoting equitable outcomes.

Our findings suggest that a successful blockchain future hinges on a three-pronged approach. First, establishing a unified legal system and robust data governance frameworks creates a secure and stable environment. Second, cost-effectiveness measures like incentives and talent development encourage business adoption and equip the workforce with the necessary skills. Finally, blockchain can revolutionise waste management for the circular economy through data tracking, transparent markets, and public databases. Further research is required to unlock its full potential.

Author's contribution

Ádám Bereczk: 34%, conceived and designed the study, collected the data, performed the analysis. Bettina Hódiné Hernádi: 33%, collected the data, edited and formatted the text, proofread the text. Gábor Mélypataki: 33%, worked on conceptualisation, the environmental and legal aspects.

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