



Non-fungible tokens: The missing ingredient for sustainable supply chains in the metaverse age?

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ABSTRACT

Non-fungible tokens (NFTs), unique digital assets on a blockchain that can represent ownership of digital or physical items, are potentially ground-breaking in their capacity for transforming the sustainability of supply chains. This paper explores and discusses how NFTs, analysed through the lens of the Technology Organisation Environment (TOE) framework, can drive supply chain sustainability and overcome the barriers to Blockchain Technology (BCT) adoption. We elucidate the unique value proposition of NFTs and explore the potential of 'phygital products' for linking digital NFTs to physical goods. Based on the existing literature and a review of real-world case studies, we propose that NFTs can (1) incentivise supply chain stakeholders to engage in more sustainable practices; (2) enhance customer willingness to pay for sustainable products; (3) provide anti-counterfeit measures; (4) support circular business model growth. A sustainable 'Mint-to-Order' production strategy starting with the creation (minting) of an NFT is proposed based on a synthesis of the findings. The use of NFTs has significant implications for both digital and physical product offerings and sustainable supply chain management (SSCM) practice making a compelling case for adoption. This paper is one of the first to explore the potential of using NFTs to drive sustainability in supply chains forming an essential component of a metaverse nexus and delineating a future research agenda.

1. Introduction

The boundaries between the physical and virtual worlds are becoming increasingly blurred. The metaverse, a collective virtual shared space, is emerging as a significant area of interest for operations and supply chain management (OSCM) scholars and practitioners (Queiroz et al., 2023; Dolgui and Ivanov, 2023). It has the potential to profoundly impact customer-business interactions, manufacturing processes and sustainable business models and supply chains (Dwivedi et al., 2022; Queiroz et al., 2023; Dolgui and Ivanov, 2023). However, a better understanding of the intricacies of this developing cyber-physical integrated world is needed (Choi et al., 2023). In accordance with Sheu et al. (2021), our comprehensive approach to SSCM integrates environmental (green), social, and economic aspects of sustainable development, aligns with the Sustainable Development Goals (SDGs) (United Nations, 2015), and emphasises the important role of all supply chain participants, including customers as members of civil society, in realising these goals.

Interactions between the metaverse and physical world are facilitated by cutting-edge technologies and smart devices creating

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platforms for a wide variety of commercial and social activities (Dwivedi et al., 2022). A development at the forefront of this interaction is blockchain technology (BCT). BCT is a key technology in the fourth industrial revolution (Industry 4.0) (Bai et al., 2020), offering a foundational layer for Web3—the envisaged next phase of the internet characterised by decentralisation and intelligent systems (Mougayar, 2016). Within the Web3 domain, the metaverse concept emerges as a distinctive application of extended reality, bridging the physical and digital realms in a way that allows for unprecedented convergence and interaction (Belk et al., 2022; Queiroz et al., 2023). The term “metaverse”, whilst often used to refer to the abstract concept of a virtual world or ecosystem in a more general, holistic sense, is also used in the context of specific metaverse projects which can vary in their objectives. For example, *Wilder World* (2023) is a specialised, photorealistic, gaming space, while *Decentraland* (2023) caters to a variety of functions including brand promotion, music events, gaming, and education via its own virtual university. This distinction is important given the current lack of interoperability among such projects, the implications of which are discussed in Section 5.2. This paper goes on to discuss opportunities for unlocking universal principals for engaging with metaverses rather than championing any propriety metaverse ecosystem.

BCT, the primary technology of Web3 ecosystems and metaverse projects like the ones outlined above, has the potential to address some of the most persistent and intractable supply chain challenges, such as product counterfeiting (Choi, 2019; Naoum-Sawaya et al., 2023), supply chain transparency (Wang et al., 2019; Dutta et al., 2020) and a range of different sustainability concerns (Saberli et al., 2019; Dutta et al., 2020; Guo et al., 2020). However, despite its potential to aid the progression toward the SDGs (Cao and Shen, 2022) and some reported successes for consumers’ willingness to pay for sustainable products supported by BCT (Kshetri, 2018; Saberli et al., 2019; Guo et al., 2020), the current value proposition for harnessing BCT for SSCM is immature and unclear to consumers, inhibiting business case justifications and, consequently, BCT adoption (Saberli et al., 2019; Kouhizadeh et al., 2021).

Ongoing innovations in the field of BCT, particularly the advent of non-fungible tokens (NFTs), may help to overcome these adoption barriers. NFTs are a novel form of blockchain-based digital asset, created in 2018 on the Ethereum blockchain (Entriken et al., 2018). Known as crypto tokens, they are underpinned by the transparency and immutability of BCT. NFTs can be attached to unique items that require ‘provable ownership’ and they can represent both physical and digital goods (Ethereum, 2022). Consequently, they serve as a key interface between the metaverse and the physical world.

Emerging real-world applications of NFTs underscore their potential value for SSCM. For example, *RTFKT* (2021) used NFTs to sell digital sneakers, with physical versions subsequently provided, demonstrating an innovative strategy for inventory management and waste reduction, key aspects of SSCM. Similarly, Adidas minted (sold) NFTs that could be exchanged for physical items within a specific time window, reducing overproduction by catering to those who value the digital asset alone (Peters, 2021). Nike’s ‘Cryptokicks iRL’ project (launched 2022) further exemplifies this, where the NFT was paired with a physical sneaker shipped post-sale, ensuring production and shipment only for sold NFTs (Blockchain Council, 2022; RTFKT, 2023). These initiatives, though nascent, highlight the timely need for deeper understanding of NFTs’ impact on SSCM. They offer novel ways to enhance physical product value, ensure secure and transparent product verification, and create unique consumer engagement opportunities. The gaming and digital art industries have also been early adopters (Dowling, 2021; Wang et al., 2021). Whitaker and Kräussl (2020) proposed that BCT can help artists retain equity in their creative works, allowing them to yield significant returns beyond the initial sale. Several NFT marketplaces have emerged such as OpenSea, Rarible, SuperRare, and Nifty Gateway (Wang et al., 2021), and NFT market value surpassed \$2 billion in 2021 (Frank, 2021). While it is envisaged that NFTs, signified by the idea of the ‘tokenisation’ of physical items, may enable a variety of new BCT applications (Regner et al., 2019), studies exploring their potential are rare (Ethereum, 2022). It remains unclear as to how NFTs will be adopted and what impact they will have on SSCM and OSCM more generally. Mithas et al. (2022) suggested that understanding how emerging technologies such as BCT can help with sustainability is part of a ‘frontier research agenda’ for addressing OSCM concerns.

The rapid development of the metaverse and BCT platforms invites further examination into its state of progress. This paper extends the growing literature on BCT for supply chains by conceptually exploring NFTs in a supply chain context. Specifically, we examine the potential of NFTs for revealing new insights into our understanding of the potential of BCT for SSCM. The TOE framework is used to help explain how NFTs may address the barriers to BCT for SSCM. The following research questions have been devised in support of the research aims:

RQ1: Can NFTs address the BCT adoption barriers to support SSCM?

RQ2: How can the integration of NFTs with physical products contribute to improving SSCM?

RQ3: How does integrating NFTs into physical supply chains facilitate the bridging of the physical-digital worlds in the metaverse era?

Section 2 of the paper presents a review of the literature on the barriers to BCT for SSCM and explores the concept of tokenisation and the novel characteristics of NFTs. Section 3 presents real-world case studies where NFTs have been linked to physical items. This leads to a conceptual exploration of the potential of NFTs for improving SSCM and a future research agenda in Section 4. Section 5 highlights some NFT-specific adoption barriers. Section 6 synthesises the findings and provides a discussion of their key implications. To conclude, key findings and recommendations for future research opportunities are summarised in Section 7.

1.1. Research methodology

We first conducted an in-depth literature review, critically examining the intersection of BCT, NFTs and SSCM. The review of BCT for SSCM focused on understanding present adoption barriers from a TOE framework perspective, a concept previously shown to support BCT adoption decision-making (Kouhizadeh et al., 2021). We then examined the emergent academic literature on NFTs which

was supplemented with a range of publicly-available, real-world use cases (Section 3), following the approach by Choi et al. (2018). The emergent insights from the NFT literature and practical case studies were organised according to the TOE framework. The framework helped identify fertile areas where the inclusion of NFTs in a BCT-enabled SSCM approach is likely to provide real-world value. This research process is outlined in Fig. 1.

A systematic approach was undertaken to search the Scopus database for published papers using the following keywords: ‘blockchain’, ‘sustainability’, ‘sustainable supply chain management’, ‘sustainable operations’, ‘BCT adoption barriers’, ‘non-fungible tokens’ ‘NFTs’ ‘tokenisation’. Following other researchers in the field, such as Dutta et al. (2020) and Govindan et al. (2024), the Scopus database was selected for its reliable and extensive research coverage. As highlighted by Govindan et al. (2024), Scopus offers a significant advantage by providing access to the latest information through daily updates, which is important for a quickly evolving field like BCT. Furthermore, Scopus has a greater focus on contemporary subject areas than other journal databases (Singh et al., 2021; Govindan et al., 2024). Whilst Web of Science (WoS) and Scopus are both strong databases for technology-focused literature, Scopus contains a larger number of exclusive journals, with about 66 % of its journals not indexed in WoS (Singh et al., 2021). To narrow the scope, we focused on the most well-established OSCM journals, such as *Decision Sciences*, *European Journal of Operations Research*, *IEEE Transactions on Engineering Management*, *International Journal of Operations and Production Management*, *International Journal of Production Economics*, *International Journal of Production Research*, *Journal of Operations Management*, *Journal of Supply Chain Management*, *Management Science*, *Production and Operations Management*, *Production Planning and Control*, *Transportation Research Part E: Logistics and Transportation*.

The review revealed a range of barriers to BCT adoption for SSCM purposes. These insights were then compared to the academic research and practitioner cases on NFTs. As highlighted by Wang et al., (2018), academic research often lags real-world applications of emerging technologies. It would be limiting to rely exclusively on scholarly articles to understand the impact of NFTs on supply chains and SSCM. Real-world case studies demonstrate the commercial viability of NFTs and their ability to capture the imagination of customers. They exemplify how NFTs can be integrated into OSCM practices, revealing key emerging themes for driving the BCT for

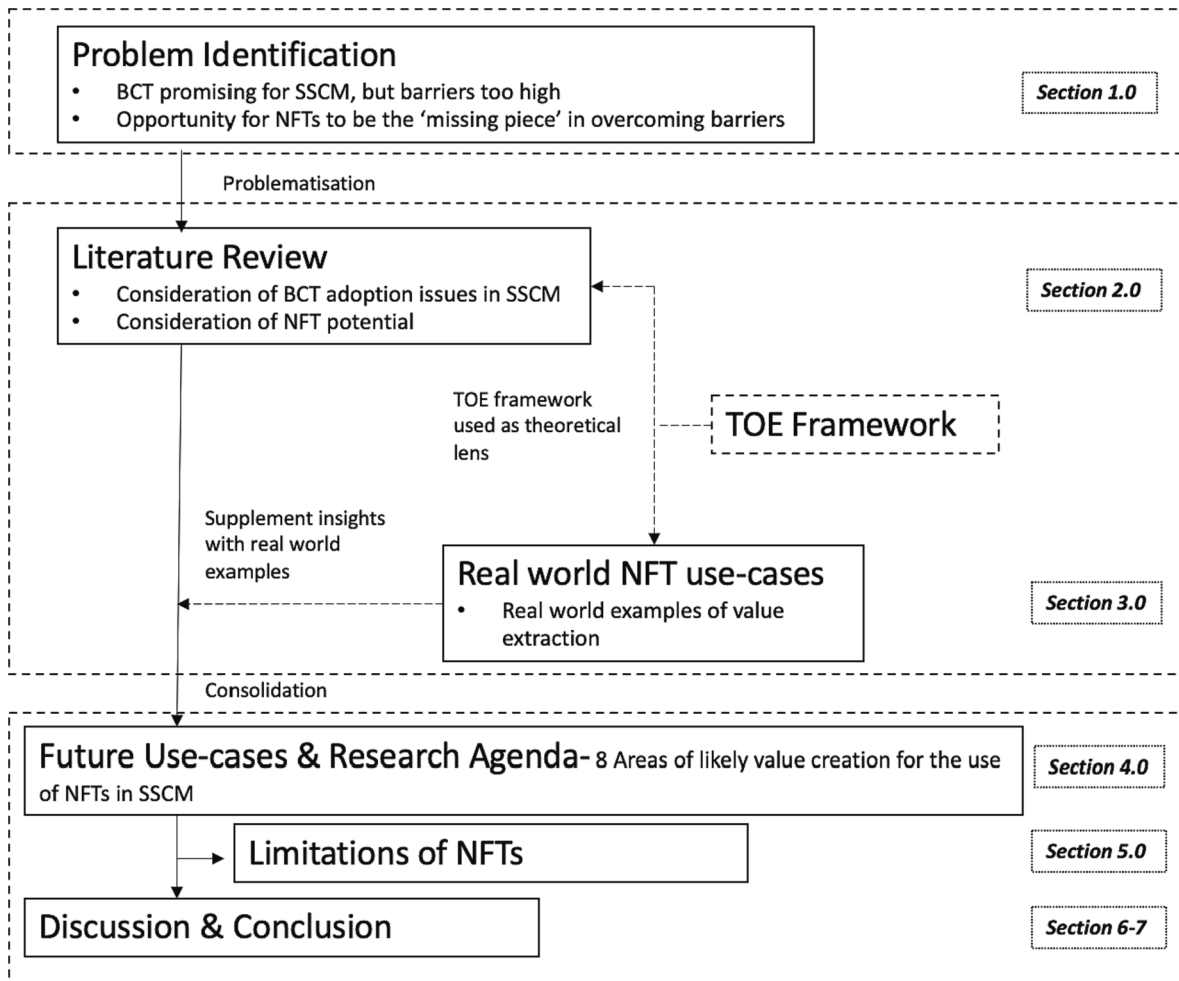


Fig. 1. Research flow for this study.

SSCM agenda and overcoming prevailing barriers. We consulted a wide range of sources to identify suitable NFT use cases such as company websites, public blockchains (e.g. Ethereum and Tezos), and digital asset databases (e.g. OpenSea and SuperRare). Third-party NFT providers (e.g. BlockBar) were analysed to gain insight into the use of NFTs in practical, supply chain contexts. We also consulted trade reports and business news outlets (e.g. Forbes) and other online publications of top consulting companies such as IBM, McKinsey, in addition to engaging with industry-specific reports and webinars from organisations such as the Business of Fashion.

1.2. Contribution statement

There have been numerous studies focusing on the influence of BCT on supply chain operations. Several of these have highlighted the challenges and obstacles to BCT adoption in both SSCM and broader OSCM contexts (cf. [Saberi et al., 2019](#); [Dutta et al., 2020](#); [Kouhizadeh et al., 2021](#)). Our study builds on this discourse by exploring the role and potential impacts of NFTs on SSCM. To the best of our knowledge, is the first to do so. We examine how NFTs can help surmount the barriers to BCT adoption in supply chains and specifically in SSCM. We identify a wealth of promising avenues for NFT application, paving the way for new perspectives and future research directions.

Building on the theoretical analysis, we examine real-world case studies and conceptualise the idea of a “Mint-to-Order” production strategy. This strategy proposes ‘minting’ (creating) an NFT first, which immediately allows customers to derive product value in the metaverse, while postponing manufacture and delivery of the physical product to a later date. We propose that this strategy will help reduce environmental waste and associated costs caused by overproduction. Lastly, our study responds to recent calls to investigate the metaverse’s role in fostering sustainable business models and addressing SSCM tensions (cf. [Queiroz et al., 2023](#)). In this context, we find NFTs to be a crucial BCT-based tool for linking physical supply chains with the metaverse, unlocking the potential of new and more sustainable business models in the metaverse age.

2. Literature review

The first stage was to design a review protocol to provide a foundation for the research. The literature review followed a systematic structure only to provide a robust grounding for the exploration of NFTs as a potential solution to present barriers. This approach was adopted out of necessity as this combination of NFTs and SSCM is too neoteric to be amenable to a systematic literature review alone and yielded only two Scopus results. The paper’s primary value and contribution lie not in the review itself but in the juxtaposition of academic insights on BCT adoption barriers with real-world NFT use cases.

Therefore, our strategy was twofold. Firstly, to establish an understanding of the barriers to BCT adoption. This is a crucial first step, as an update is required given the rapidly changing nature of this field. Secondly, we supplemented this body of knowledge with papers pertaining more generally to NFTs in the supply chain. This allowed us to synthesise insights by considering the literature for both the problem (technology adoption barrier) and the potential solution (NFTs). These and additional papers added through snowballing ensured a sufficiently broad and inclusive foundation of key literature. The literature search spanned from 2015, when discussions concerning the application of BCT in supply chains first emerged, to September 2023. The process is depicted in [Fig. 2](#).

2.1. BCT for SSCM

The mechanics of BCT systems are well-documented in the literature (cf. [Wang, et al., 2018](#); [Treiblmaier, 2018](#)). Each block represents transaction data, validated by a peer-to-peer network before being added to the blockchain ([Hald and Kinra, 2019](#); [van Hijfte, 2018](#)). The decentralised nature of BCT ensures that no single entity controls the data ([Wang et al., 2018](#)). The Ethereum

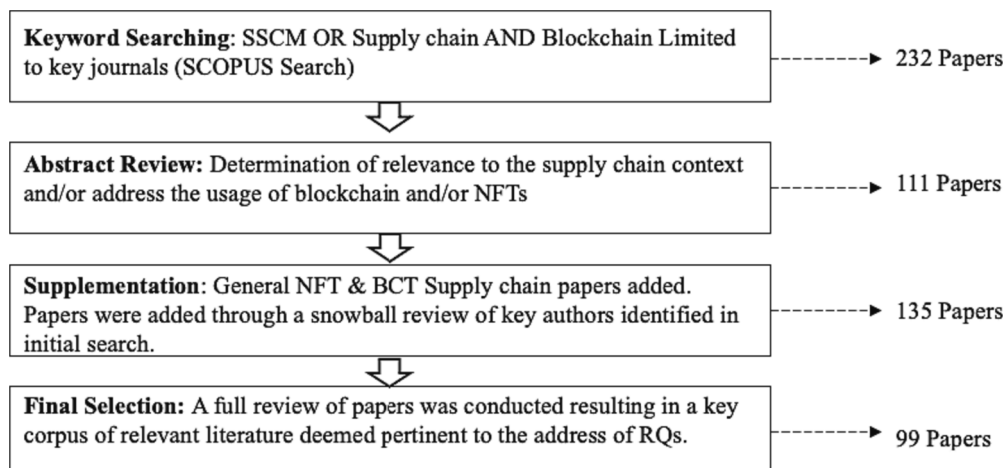


Fig. 2. Systematic Literature Review Process.

blockchain introduced ‘smart contracts’ (Buterin, 2013), extending the scope of BCT beyond cryptocurrency and enabling autonomous contract execution between parties (van Hijfte, 2018). This innovation increased BCT’s relevance in supply chain contexts (Wang et al., 2018).

Table 1
BCT adoption barriers in sustainable supply chains ().

Barrier	Description	Sources
T1 - Security	BCT enhances security but concerns about hacking and breaches persist. Privacy is a key concern for organisations and customers.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Menon and Jain, 2021; Govindan et al., 2023; Mathivathanan et al., 2021; Sodhi et al., 2022; Wong et al., 2023; Yadav and Kumar, 2023)
T2 - Access	Requires robust internet and IT infrastructure; may not align with existing systems, especially across international supply chains.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Menon and Jain, 2021; Mathivathanan et al., 2021; Sodhi et al., 2022; Wong et al., 2023; Yadav and Kumar, 2023)
T3 - Negative perceptions	Negative public perception due to BCT’s association with crypto, dark web, and environmental concerns.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021)
T4 - Immutability	BCT’s immutability means incorrect records remain, even if corrected.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Sodhi et al., 2022; Yadav and Kumar, 2023)
T5 - Immaturity	Scalability issues arise from BCT’s immaturity, challenging its core features.	(Saberi et al., 2019; Menon and Jain, 2021; Sodhi et al., 2022; Tiwari et al., 2023; Yadav and Kumar, 2023)
O1 - Financial constraints	High integration costs: focal companies and/or supply chain partners may not have the financial resources available to commit to the BCT.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Menon and Jain, 2021; Govindan et al., 2023; Mathivathanan et al., 2021; Sodhi et al., 2022; Naoum-Sawaya et al., 2023; Ahmed and MacCarthy, 2023)
O2 - Lack of managerial commitment	Managers may lack long-term SSCM commitment, leading to uncertainty about BCT’s role in innovating sustainable business models.	(Menon and Jain, 2021; Mathivathanan et al., 2021; Sodhi et al., 2022)
O3 - Lack of organisational policies	Organisations need to assess how BCT fits with existing processes and whether new policies are needed to support integration.	(Wang et al., 2018; Saberi et al., 2019; Yadav and Kumar, 2023)
O4 - Lack of knowledge and expertise	Lack of technical expertise about BCT and SSCM.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Menon and Jain, 2021; Govindan et al., 2023; Mathivathanan et al., 2021; Sodhi et al., 2022; Ahmed and MacCarthy, 2023; Tiwari et al., 2023; Wong et al., 2023; Yadav and Kumar, 2023)
O5 - Organisational culture	Challenges relating to the blockchain trilemma all stem from the immaturity of the technology and potential incompatibilities with existing digital infrastructure and associated culture.	(Wang et al., 2018; Saberi et al., 2019; Menon and Jain, 2021; Mathivathanan et al., 2021; Sodhi et al., 2022)
O6 - Inertia	Fear of change and reluctance to shift from traditional, centralised systems to BCT.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Mathivathanan et al., 2021; Sodhi et al., 2022)
O7 - Lack of benchmarks	Lack of industry standards and metrics for SSCM performance and associated BCT usage.	(Wang et al., 2018; Saberi et al., 2019; Menon and Jain, 2021; Wong et al., 2023)
E1 - Lack of customer motivation to adopt BCT and make sustainable purchases	Uncertainty in customer demand for BCT-backed SSCM products, services or initiatives. Also concerns about privacy being compromised.	(Wang et al., 2018; Saberi et al., 2019; Wankmüller et al., 2023)
E2 - Lack of supply chain alignment	Collaboration challenges hinder BCT integration across supply chains.	(Wang et al., 2018; Saberi et al., 2019; Menon and Jain, 2021; Mathivathanan et al., 2021; Yadav and Kumar, 2023; Ying et al., 2023; Zhu et al., 2023)
E3 - Information disclosure between supply chain partners	Supply chain partners may be reluctant to share confidential information with each other.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Menon and Jain, 2021; Mathivathanan et al., 2021; Tan et al., 2023; Yadav and Kumar, 2023)
E4 - Integrating BCT and SSCM	Integrating BCT with current business processes and sustainability practices can be challenging.	(Menon and Jain, 2021; Yadav and Kumar, 2023)
E5 - Cultural differences of supply chain partners	The different geographical or organisational culture of supply chain partners and other stakeholders can impede BCT.	(Wang et al., 2018; Saberi et al., 2019; Mathivathanan et al., 2021; Yadav and Kumar, 2023)
E6 - Lack of governmental policies	There is regulatory uncertainty for BCT internationally.	(Wang et al., 2018; Saberi et al., 2019; Balci and Surucu-Balci, 2021; Menon and Jain, 2021; Mathivathanan et al., 2021; Wong et al., 2023; Yadav and Kumar, 2023)
E7 - Market competition and uncertain benefits	Uncertainty in the competitive advantage BCT adoption would give due to unclear customer demand etc.	(Saberi et al., 2019; Balci and Surucu-Balci, 2021; Mathivathanan et al., 2021; Sodhi et al., 2022; Wong et al., 2023; Yadav and Kumar, 2023)
E8 - Lack of external stakeholder involvement	Limited external promotion and incentives for BCT in SSCM from NGOs, trade bodies etc.	(Saberi et al., 2019; Balci and Surucu-Balci, 2021)
E9 - Lack of industry BCT standards	There is a lack of industry standards for how to adopt BCT in an ethical and safe manner.	(Wang et al., 2018; Saberi et al., 2019; Yadav and Kumar, 2023)
E10 - Lack of rewards and incentives	Insufficient incentives and reward systems deter customers, organisations, and suppliers from embracing BCT in SSCM.	(Saberi et al., 2019; Sodhi et al., 2022; Zhu et al., 2023)

adapted from Kouhizadeh, et al., 2021

The transparency provided by BCT has the potential for addressing numerous social, environmental and economic problems (Sabeti et al., 2019; Guo et al., 2020; Choi et al., 2022) and can support circular supply chains (Meier et al., 2023). BCT helps facilitate trust (Dubey et al., 2020; Brookbanks and Parry, 2022; Iyengar et al., 2023) and can improve data management, increase accountability and verify corporate sustainability claims (Kshetri, 2018; Sabeti et al., 2019). It can also help provide product provenance assurances (Nowiński and Kozma, 2017; Helo and Hao, 2019; Choi et al., 2020; Biswas et al., 2023), store SSCM certification information, and improve consumer welfare and value (Nowiński and Kozma, 2017; Wang, et al., 2019; Manupati et al., 2020; Iyengar et al., 2023). Choi (2019) demonstrated that BCT implementation in the diamond industry yielded significant benefits when customer value was primarily based on diamond authenticity and certification, rather than traditional retail convenience. Subsequently, it can help support more sustainable business models that rely on trust, such as product rental services (e.g. luxury handbags) (Choi et al., 2020) or product remanufacturing (Niu et al., 2022).

The ability of BCT to improve supply chain provenance can also help to reduce supply corruption and has been identified as an ‘emancipatory technology’, helping to foster trust and empathy with customers. This is demonstrated in the work of George et al. (2022), where BCT was used in conjunction with storytelling methods to create ‘multi-dimensional provenance’. Both supply chain transaction details and images and biographies of miners in the gemstone industry were stored on the blockchain, helping to humanise the supply chain, and promote more ethical purchasing practices.

Counterfeiting has a debilitating effect in sectors from luxury goods to pharmaceuticals and food (Ellis et al., 2017; Wang et al., 2019; Koh et al., 2020; Danese et al., 2021; Ghadge et al., 2021; OECD, 2021; Vu et al., 2021). BCT can act as an anti-counterfeiting solution (Kshetri, 2018; Cole et al., 2019; Helo and Hao, 2019; Sabeti et al., 2019; Koh et al., 2020; Vu et al., 2021; Shen et al., 2022), particularly when sales channels are unreliable or customers struggle to distinguish between authentic and counterfeit products (Li et al., 2021).

Successful BCT supply chain pilot studies have been reported in the literature (cf. Wang et al., 2018; van Hoek, 2019), yet adoption in manufacturing industries is still very low (Wong et al., 2023). Sohdi et al. (2022) have posited that initial enthusiasm can give way to disillusionment as managers grapple with the practicalities of adoption which may be divorced from their expectations (Sodhi et al., 2022). Examples of where it has been employed to drive ethical supply chain practice are few. Notably, BCT saw early adoption with pilots in the coffee industry for fairer, faster payments to small suppliers (Wang, et al., 2019). Pilots have since evolved into the development of comprehensive BCT platforms. For instance, Dimitra, a global AgTech company, has recently announced a partnership with the Solok Radjo cooperative, which represents over 3,000 coffee farmers in Indonesia. Through Dimitra’s BCT platform, Solok Radjo can now easily demonstrate its commitment to eco-friendly farming practices. Proof of these practices, coupled with meeting stringent food safety and export standards, opens up opportunities in new international markets, increasing profitability (Hooper, 2023). BCT has also been used to support ethical cobalt sourcing for electric car batteries (Hastig and Sodhi, 2020). More generally, within the realm of supply chain applications, Vechain, OriginTrail, and Morpheus.Network have forged connections with prominent organisations. Vechain specialises in digital identity and supply chain management, OriginTrail excels in data interoperability and transparency, and Morpheus.Network concentrates on automating global supply chains (Vechain, 2023; OriginTrail, 2023; Morpheus Network, 2023). Vechain, who recently announced a partnership with Walmart China, focused on enhancing supply chain transparency and efficiency. Vechain’s IoT and blockchain capabilities allow Walmart to monitor temperature-sensitive products in transit assuring food safety and reducing food waste (Lilian, 2023).

Despite these advances, current BCT solutions lack the compelling value proposition necessary for widespread adoption. An illustrative case is that of TradeLens, an ambitious attempt at a ubiquitous platform that was recently discontinued (Maersk, 2022). This discontinuation further underscores that all of the necessary pieces might not yet be in place among the current offerings. These specific initiatives, while promising, fall short in addressing the pivotal issue of customer engagement, a prerequisite for broad

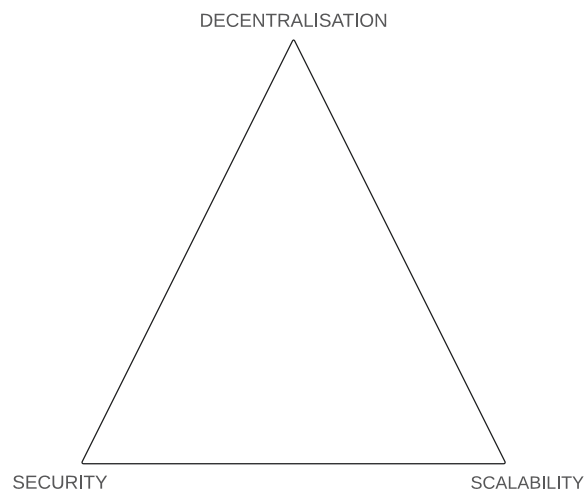


Fig. 3. The blockchain scalability trilemma.

acceptance. A recent whitepaper from Vechain conspicuously recognises this gap, drawing connections between gamification, NFTs (phygital, etc.), and sustainability, while presenting plans to introduce NFTs (Vechain, 2023). This perspective aligns with the central proposition of our paper, which posits that the fusion of gamification and NFTs within the metaverse (Web 3) can serve as a catalyst, incentivising consumers towards more sustainable, ethical choices whilst acknowledging the limitations of current solutions.

2.2. Barriers to BCT for SSCM adoption

The potential of BCT has been well explored in the literature. However, there are several challenges and barriers limiting its adoption as an SSCM solution (Saberi et al., 2019; Kouhizadeh et al., 2021). The TOE framework (Tornatzky et al., 1990) was adopted by Kouhizadeh et al. (2021), Han and Fang (2023) and Yadav and Kumar (2023) as the theoretical lens for explaining BCT for SSCM adoption barriers. The framework suggests that technology adoption depends on three key aspects: technological (T), organisational (O), and environmental (E) factors. ‘T’ encompasses technological capability, complexity, and availability. ‘O’ involves intra-organisational priorities and considerations. ‘E’ relates to industry characteristics, such as regulations, inter-organisational relationships, and market competition (Tornatzky et al., 1990). The following section presents a contemporary update of some of the key barriers to BCT adoption for SSCM, in accordance with the typology proposed by Kouhizadeh et al. (2021). A summary of barriers is presented in Table 1.

From a technological perspective, the immaturity of BCT presents several challenges that may also impact NFT adoption (Saberi et al., 2019; Wang et al., 2019; Kouhizadeh, et al., 2021). The ‘blockchain scalability trilemma’ (see Fig. 3) involves balancing scalability, decentralisation, and security, with improvements in one potentially compromising the others (Zhou et al., 2020). For example, increasing transaction speeds without sacrificing decentralisation and security (the key features of BCT) can be a major challenge (Zhou et al., 2020). Another scalability concern that is often overlooked in the SSCM literature is the negative environmental impact of some blockchains. Some BCTs, like Bitcoin, use energy-intensive ‘proof-of-work’ consensus mechanisms (*Ibid*). A ‘proof-of-stake’ mechanism is an alternative approach that takes account of energy efficiency (van Hijfte, 2018). The Ethereum blockchain completed migration to a proof-of-stake protocol in September 2022, reducing energy consumption by 99.95 %. (Ethereum, 2023). Other energy efficient protocols include ‘proof-of-authority’ which is the consensus mechanism behind popular supply chain BCT platforms such as Vechain (Vechain, 2023).

There are numerous organisational barriers to BCT for SSCM adoption highlighted in the literature. One that is particularly pertinent to later discussions about NFTs is the lack of sustainable business models for BCT (Saberi et al., 2019). Businesses are unsure whether utilising BCT for a sustainable supply chain aspiration will translate into a competitive advantage (Kouhizadeh, et al., 2021) and are uncertain that investment in SSCM and supporting technologies will be “compensated by their customers” (Saberi et al., 2019, p. 2126). High setup costs can limit adoption in industries with a strong cost focus (Kumar et al., 2020). Choi and Luo (2019) found that whilst BCT could improve social welfare it may reduce profitability due to the associated adoption costs. They suggested government intervention in the form of subsidies for retailers who adopt BCT, or the waiving of certain environmental taxes, could make adoption more financially viable.

In terms of the external environmental context, there are several supply-chain wide barriers to adoption. Central to these, and echoing the aforementioned sustainable business model challenges, is an uncertain customer demand for sustainable products and practices (Kouhizadeh, et al., 2021; Saberi et al., 2019). Clear value propositions are crucial to successful business model development (Osterwalder and Pigneur, 2010). The value proposition of BCT for SSCM for consumers remains unclear (Kouhizadeh, et al., 2021; Saberi et al., 2019).

Other external barriers include the absence of supply chain stakeholder incentivisation for adopting BCT for SSCM (Kouhizadeh, 2020). Integrating BCT with existing supply-chain-wide practices and technologies is time consuming and requires a coordinated effort by supply chain partners (Cai, et al., 2021). BCT can curtail opportunistic or deceptive actions in transactional supply chain relationships (Cai et al., 2021) and foster enhanced collaboration, communication, and coordination among supply chain partners (Saberi et al., 2019; Kouhizadeh et al., 2021). Yet, its adoption may be hindered if these collaborative elements are absent (*Ibid*).

There is limited support from external stakeholders such as NGOs, trade bodies, and governments on harnessing BCT to create sustainability-based value (Saberi et al., 2019). Furthermore, governmental BCT regulations are vague and varied, exacerbating adoption uncertainty (Saberi et al., 2019). For example, while China banned cryptocurrency transactions in 2021 (BBC, 2021), El Salvador embraced Bitcoin as legal tender (Frankel, 2021). The US remains largely unregulated, with officials likening the crypto space to “the Wild West” (The Financial Times, 2021). Such varying regulations, combined with geographic and cultural differences among supply chain partners, can intensify adoption barriers (Saberi et al., 2019; Kouhizadeh et al., 2021).

The following section focuses on the emergent potential of NFTs within the BCT domain, postulating their capacity to ameliorate the present BCT adoption impediments.

2.3. Tokenisation and NFTs

This section explores the potential of tokenisation and NFTs in overcoming the key barriers to BCT for SSCM implementation. ‘Tokenisation’ or ‘Tokenomics’ is a rapidly developing area of BCT and enables the conversion of ownership rights into digital crypto tokens, managed by blockchain smart contracts (Kumar et al., 2020; Di Angelo and Salzer, 2020; Chittoda, 2019). Tokens can be fungible or non-fungible (Chittoda, 2019; Bal and Ner, 2019). Fungible assets, like fiat (government issued) currency and crypto coins, are exchangeable and divisible without affecting their value (Bal and Ner, 2019; Ethereum, 2022), whereas non-fungible assets e.g original paintings, possess unique, indivisible, and non-interchangeable characteristics (*Ibid*). NFTs represent a ground-breaking

innovation in BCT, as they allow for the representation and ownership of unique assets (both digital and physical), unlike traditional cryptocurrencies that are fungible (Watanabe et al., 2019). Kumar et al. (2020) suggested that the progress of BCT will be shaped by developments in frameworks and tools related to token design.

NFTs, introduced in 2018 with the ERC-721 standard on the Ethereum blockchain (Entriken et al., 2018), also allow for fractional ownership, benefiting creators and fractional owners beyond the original sale (Ethereum, 2022). Semi-fungible tokens, like ERC-1155, emerged shortly after NFTs and support both fungible and non-fungible tokens (Ibid). They can enable categories of tokens that can be “1 of n with a serial number or slightly different metadata” (EOSIO, 2021). This latest development shows potential for small product ranges that share the same unique characteristics (e.g. a limited-edition clothing collection or a particular year of vintage wine). The process of creating an NFT is known as ‘minting’ (DiAngelo and Salzer, 2020). Another key NFT-related term is ‘forging’, which describes the process of adding additional transaction data to an existing NFT blockchain record post-minting and is used, for example, when customers claim the physical product attached to an NFT token, so that the physical item is only claimed once (RTFKT, 2023).

Tokenisation can help support the goals of SSCM by incentivising sustainable behaviour using crypto tokens (Esmaeilian et al., 2020; Saberi et al., 2019). There have been notable examples of start-ups which reward customers with crypto tokens for purchasing carbon-neutral products or recycling plastics (Esmaeilian et al., 2020). Some authors have warned that tokens must be clearly defined in terms of what they represent, as their value depends on supply, demand, and community belief (Di Angelo & Salzer, 2020). The existing research on tokenisation in supply chains has predominantly focused on fungible tokens like ERC-20. Studies on NFT usage in supply chain contexts are relatively scarce (Regner et al., 2019). However, Wankmüller et al. (2023) recently demonstrated the use of NFTs to individualise plastic bottles in a recycling system pilot study, incentivising better recycling behaviours. NFT usage allowed detailed tracking and prevented fraudulent behaviour (e.g. repeated scans) which fungible tokens could not enable. Scholars, such as Van Nguyen et al. (2023), have highlighted the potential of NFTs to support circular business models (e.g. rental and resale in the fashion industry), whilst also noting the need for further research in this area.

In other application areas, NFTs are also showing promise for addressing some enduring and obstinate supply chain challenges. For example, a recent study in healthcare supply chains proposed the use of NFTs to provide unique identification and individual ownership representation of medical devices, thereby reducing the risk of counterfeiting and improving transparency (Gebreab et al., 2022). Similarly, in a proof-of-concept study, dos Santos et al. (2021) proposed NFT usages in high-end wine production, where unique harvest properties are crucial for determining product value and where counterfeiting threats are present. These examples underscore the unique capabilities of NFTs in enabling precise tracking and ownership management in diverse supply chain contexts.

Ethereum is one of the most popular blockchains for smart contracts (Chittoda, 2019; Di Angelo and Salzer, 2020). However, there are some blockchains that have emerged in addition to Ethereum which support both smart contracts and tokens (see Table 2 below for notable examples). The Hyperledger blockchain, used successfully in pilot studies in both shipping and food supply chains by IBM, supports smart contracts (Wang et al., 2019). However, their own token standards are still under development (Androulaki et al., 2021). It is worth noting that the tokenisation of assets requires complementary and enabling decentralised applications (DApps), that provide a user-friendly interface for issuing and exchanging tokens for specific purposes (van Hijfte, 2018).

The characteristics of NFTs that make them unique and of interest in the discourse of BCT for SSCM are explored further in the following sections.

2.4. Scarcity: The secret ingredient of NFTs

NFTs provide verifiable ownership of unique items, where the item value is often determined by properties such as ownability, authenticity, and scarcity (Ethereum, 2022). Unlike BCT, NFTs inherently limit ownership, creating a supply shortage that translates to increased demand. The ‘scarcity heuristic’ explains this phenomenon, where items perceived as rare are valued more highly (Worchel et al., 1975; Mittone and Savadori, 2009; Chou, 2021). Examples such as Facebook’s initial Harvard-only access and Clubhouse’s invitation-only model for Apple users illustrate how scarcity enhances perceived value and can act as a powerful psychological driver that influences human perception (Worchel et al., 1975; Chou, 2021).

NFTs have rapidly gained popularity in the creative and entertainment sectors, especially in art, music and gaming (Wang et al., 2021, p. 12). Digital artist Mike Winkelmann, better known as Beeple, exemplifies the transformative potential of NFTs. Before 2020, his artworks sold for \$100 each. However, with the introduction of exclusive NFTs of his creations, prices began at \$66,000 (Tarmy and Kharif, 2021). By March 2021, an NFT of his artwork fetched \$69.3 million at Christie’s auction house, ranking it among the most expensive artworks ever (Dowling, 2021). This difference underscores the ability of NFTs to amplify the inherent value of an item, driven by its rarity, authenticity, and exclusivity. Another compelling application lies in event ticketing. NFT-based ticketing systems can help to address long-standing issues such as ticket touting and counterfeiting. NFT tickets not only improve security and

Table 2
Notable blockchains which support NFTs.

	Ethereum	Tezos	EOSIO	Flow	Solana
Cryptocurrency coin	Ether (ETH)	TEZ (XZT)	EOS (EOS)	FLOW (FLOW)	SOL (SOL)
Fungible token standard	ERC-20	FA1.2 (TZIP-7)	N/A	flow-ft	N/A
Non-fungible standard	ERC-721	N/A	N/A	flow-nft	N/A
Multi token standard	ERC-1155	FA2 (TZIP-12)	dGoods	N/A	SPL token
Consensus protocol	Proof-of-stake	Proof-of-stake	Delegated proof-of-stake	Proof-of-stake	Proof-of-history/proof-of-stake.

Table 3

Real-world case studies of companies linking NFTs to physical products.

Industry	Year	Companies involved	Case description	Key insights	Blockchain/ Auction platform	Source
Footwear	2021	RTFKT	RTFKT design studio collaborated with digital artist Fewocious to sell digital NFT sneakers that were sold with a physical version of the sneaker that was delivered for buyers at a later date. All NFT holders were 'airdropped' wearables to use in Decentraland blockchain metaverse	- Delivery: NFT first, physical item second - NFT version of the product wearable in the metaverse.	Ethereum	(RTFKT, 2021)
Clothing	2021	Overpriced	A clothing company (Overpriced) operating as an 'NFT-first and physical-goods-second brand', launched a collection of high-end hooded sweatshirts verified by NFTs. Possessing the NFT allows for limitless physical hoodie replacements.	- Delivery: NFT first, physical item second - NFT holder given physical product lifetime guarantee.	Ethereum	(Tong, 2021).
Fragrance	2021	Danilo Lauria	Visual artist, Danilo Lauria, launched an NFT fragrance called L'eau de Distance in conjunction with perfume expert, Gunu Kapoor (PrivéLabel), 10 NFTs were for sale at 300 Tezos each (\$1,659 at the time of sale) and with the promise of a bottle of real perfume. However, the launch was not successful due to the failure of the Hic et Nunc platform.	- Delivery: NFT first, physical item second - Project failed due to discontinuation of the Hic et Nunc platform.	Tezos Hic et Nunc	(Kelly, 2021)
Spirits	2021	William Grant and Son x BlockBar	Glenfiddich and BlockBar created NFTs for 15 bottles of 46-year-old whisky, sold at \$18,000 each. The whisky bottle remained in the company's custody until the NFT holder claimed it, at which point the associated NFT was 'burned' (destroyed), establishing a novel approach to maintaining authenticity and provenance of luxury physical goods.	- Delivery: Customer owns the NFT only until it is exchanged for the physical item, at which point the NFT is 'burned' (destroyed) and the physical product is shipped. - Physical product stored in temperature-controlled facility in Singapore.	Ethereum Blockbar	(BlockBar, 2021)
Clothing	2021	Adidas in partnership with Bored Ape Yacht Club, Punks Comics, and GMoney	Adidas Originals launched its 'Into the Metaverse' NFT collection in Dec 2021. 30,000 NFTs were minted that could be exchanged for physical items at a later date (early 2022) that included exclusive Adidas original tracksuit tops. There was a limited 'physical merch claim window' within which the physical items had to be claimed.	- Delivery: NFT first, physical item second (only if redeemed within the limited time window).	Ethereum OpenSea	(Peters, 2021)
Wine	2021	Cult Wines x Chateau Angélus	Cult Wines collaborated with Bordeaux's famed winery, Chateau Angélus, selling an NFT of a 3D animated artwork of the iconic Chateau Angélus bells with an associated physical asset of One barrel of Chateau Angélus Bordeaux En Primeur 2020. The NFT sale also included a virtual tasting with the winery's CEO.	- Delivery: NFT minted by Cult Wines then transferred to customer. - Physical product stored in temperature-controlled facility by Cult Wines, following bottling by the winemaker.	Ethereum OpenSea	(DeSimone & Jenssen, 2021)
Jewellery	2022	Tiffany & Co	Tiffany & Co. sold 250 'NFTiffs' as digital passes for CryptoPunks (NFT digital art) holders to buy custom pendants inspired by its Punk NFT. Designers use gemstones and enamel colors to match the	- Delivery: NFT first, physical item second. - Production process highly customised based on the NFT art.	Chain.com	(Tiffany & Co, 2022)

(continued on next page)

Table 3 (continued)

Industry	Year	Companies involved	Case description	Key insights	Blockchain/ Auction platform	Source
Footwear	2022	Nike (RTFKT)	<p>CryptoPunk's attributes. NFTiffs went on sale in August, clients received a render in October 2022 with physical delivery scheduled for early 2023. The physical package includes a pendant, chain, certificate of authenticity, and Tiffany & Co. packaging.</p> <p>Nike acquired RTFKT in December 2021 and a year later launched the 'Cryptokicks iRL' project which was marketed as the 'first smart sneaker/native web3 sneaker'. The NFT came with a physical sneaker that was shipped after the NFT sale. Each physical item was fitted with a Near Field Communication (NFC) chip that allowed NFC-NFT linking via the Cryptokicks mobile app for authentication. The sneakers could also be 'tried on' in advance using a snapchat augmented reality (AR lens). The collaboration saw the introduction of the 'Cryptokicks iRL leaderboard' demonstrating a clear use of gamification techniques. Another notable point is that Nike x RTFKT receive 5 % of any future sales on NFT marketplace, OpenSea.</p>	<p>- Delivery: NFT first, physical item second.</p> <p>- NFT linked to physical product via NFT chip facilitated by mobile application.</p>	Ethereum OpenSea	(RTFKT, 2023; Blockchain Council, 2022)
Automotive	2022	Alfa Romeo	<p>The Tonale SUV model was claimed to be the first vehicle on the market that came complete with an NFT digital certificate. The NFT could register vehicle data to provide an immutable record of service history to guarantee the vehicle had been properly maintained to help hold value for future resale.</p>	<p>- NFT comes with the physical purchase.</p>	Not publicly disclosed	(Alfa Romeo, 2023)
Clothing	2022	Gap	<p>The clothing retailer introduced a 'gamified experience', launching a series of digital hoodie art NFTs in collaboration with digital artists that had different levels of rarity and price points. Purchases included a physical Gap sweatshirt.</p>	<p>- Delivery: NFT first, physical item second.</p>	Tezos Objkt.com	(Sato, 2022)
Spirits	2022	Patrón	<p>The Tequila producer sold NFTs that corresponded to a physical bottle of its limited-edition Chairman's Reserve tequila. Limited to 150 bottles, the NFTs acted as digital receipts, verifying the ownership that could be transferred, sold, or redeemed for the physical bottle from the company which handled the storage of the product.</p>	<p>- Delivery: Customer owns the NFT only until it is exchanged for the physical item, at which point the NFT is 'burned' (destroyed) and the physical product is shipped.</p> <p>- Physical product stored in temperature-controlled facility in Singapore.</p>	Ethereum Blockbar	(Patron, 2022)
Watches	2022	Breitling	<p>Breitling's NFT-based Digital Product Passport offers an enriched ownership experience, facilitating a comprehensive view of a watch's history and provenance. Owners receive priority access to exclusive events and limited-edition releases, adding value beyond the initial purchase. The passport also simplifies aftercare with service</p>	<p>- Offers NFT-based Digital Product Passports for customers.</p> <p>- Enables access to exclusive brand events.</p>	Arianee/ Ethereum	(Arianee, 2023)

(continued on next page)

Table 3 (continued)

Industry	Year	Companies involved	Case description	Key insights	Blockchain/ Auction platform	Source
			notifications and direct management of personal collections through a Breitling account. Additionally, it includes a warranty extension, ensuring long-term customer satisfaction and brand loyalty.			
Fragrance	2023	Danilo Lauria	Building on lessons learned from the L'eau de Distance project, Danilo Lauria created the 'Ethereum Scent' which features a one-of-a-kind exclusive physical bottle of perfume with associated NFT. Due to be sold/minted and shipped in 2023.	- Delivery: NFT first, physical item second.	Ethereum SuperRare	(SuperRare, 2023)

immutability but can become collectibles (YuanJiang and Zhou, 2022). For example, high-profile music festival, Coachella, recently utilised NFTs for its 'Coachella Keys Collection' which gave ten owners lifetime festival passes, exclusive merchandise and experiences, including in the metaverse (Marr, 2022). NFTs also support direct-to-consumer (DTC) supply chains in personality-driven markets by creating exclusivity. For instance, prominent sporting figures such as Cristiano Ronaldo have issued NFTs in partnership with crypto and NFT exchange, Binance, that go beyond digital collectibles, offering customers exclusive signed merchandise (Binance, 2022).

The literature review provides a contemporary overview of the barriers to BCT for SSCM adoption. It has introduced the concept of NFTs and reviewed the emergent literature on the subject, which has largely focused on the commercial success of NFTs in a digital-only capacity, with little research focusing on NFTs as an augmentation of a physical product offering. In order to redress this balance inherent in the literature, we supplement our review with real-world examples that illustrate some ways in which NFTs have been used to represent physical products to date. The use cases we consider are explicitly product-centric, and, therefore, applicable to a supply chain context. This informs our conceptual discussions in Section 4, where we propose potential directions for NFT usage in future SSCM practices.

3. NFTs for physical items: Real-world case studies

Real-world examples where NFTs have been linked with physical items are scarce (Ethereum, 2022). There is scant empirical evidence with which we can assess the true impact of NFTs on the representation and authentication of physical items in supply chain contexts. However, there are some early pilot programmes that have surfaced since 2021. These types of product offerings are known as "phygitals" (Makridis, 2022) or 'asset-backed NFTs' (BlockBar, 2022). Both start-ups and established companies across a range of industries have begun to explore the potential of linking NFTs to physical products. The focus of these programmes ranges from using NFTs to provide an immutable record of automotive service history to luxury goods authentication. Table 3 presents a summary of notable use cases. Given the limited number of practical examples available, we have used a broad and inclusive set of criteria for case selection: we looked for cases with a digital and physical product and we prioritised a breadth of industry coverage to juxtapose contextually distinct use cases. The examples span a broad range of industries, although the luxury sector is over-represented, aligning with the prior literature noting the suitability of NFTs for luxury supply chains (dos Santos et al., 2021).

The exploration of these emerging practices supplements the knowledge derived from the literature review. It provides valuable insights into the increasing integration of physical supply chains with digital metaverse activity. A summary of key insights are as follows: **1) sequential delivery:** the delivery of NFTs and physical items follows a consistent pattern across the cases, with the digital representation of the product (NFT) delivered to customers first, followed by the shipment of the physical item. **2) metaverse-supply chain integration:** some cases demonstrate the use of NFT versions of physical products that are useable or 'wearable' within the metaverse, highlighting the potential for innovative digital-physical interactions with supply chains and digital operations. **3) Secure storage and NFT redemption:** the luxury wines and spirits case studies indicated that the NFT serves as 'proof of ownership' until exchanged for the physical item, at which point the product is stored in temperature-controlled conditions by the third-party companies facilitating the NFT sale (e.g. see Cult Wines and BlockBar cases). Once exchanged, the NFT is 'burned' (permanently removed from circulation). **4) Limited physical product redemption windows:** This practice allows customers to choose whether to claim the physical product or to derive value solely from the NFT (digital product) in the metaverse. By creating a desirable metaverse product, companies can potentially reduce physical manufacturing and associated inventory costs if the physical product remains unclaimed. **5) Third-party blockchain (TPBs) provider risks:** The failure of the Hic et Nunc BCT (NFT) platform is one case study that highlights the challenges organisations face when relying on TPBs for NFT-related projects within their supply chains. This stresses the need to mitigate risks by thoroughly evaluating third-party providers to ensure their stability. Taken as a whole, these use-cases provide a blueprint for conceiving and designing viable ways of using the technology. While the case studies do not necessarily directly address

how NFTs can be used to overcome the barriers to BCT for SSCM, they do demonstrate their commercial viability. They shed light on emerging practices that have important implications for SSCM and offer insight into potential pathways for addressing adoption barriers.

4. NFTs for SSCM: A future research agenda and propositions

In this section, we propose a future research agenda for the advancement of BCT in SSCM through the adoption of NFTs. We synthesise the insights from the literature review and the emerging themes derived from the case studies leading to eight propositions that capture how NFTs can aid in advancing SSCM. To demonstrate the value of each proposition, we will conclude each subsection with a short discussion on how these align with current SSCM enablers and barriers discussed across the literature. We also relate the propositions to relevant UN SDGs.

4.1. NFTs as accessible receipts of sustainable purchases

Although the existing literature suggests BCT can address transparency issues in supply chains, organisations struggle translating BCT-enabled, sustainability-focused supply chain designs into clear value propositions for consumers (Saberli et al., 2019). Successful business models satisfy a consumer need or desire with a precise and unambiguous value proposition (Osterwalder and Pigneur, 2010). We propose that NFTs enable traceability and SSCM data to be communicated in an accessible format for end users in a way that represents a clear value proposition empowering them to make informed sustainable consumption decisions and providing a proof-of-ownership reward mechanism for making a sustainable purchase.

A recent study proposed a directed acyclic graph (DAG) token design for traceability within supply chains. The transaction history of ERC-721 tokens on Ethereum can be retrieved within a matter of seconds without having to explore the whole blockchain. This was previously a time-consuming activity (Watanabe et al., 2019). These improvements in transaction tracking have the potential to enable customers to immediately access and verify SSCM credentials stored on the blockchain in-store.

Enhanced capabilities in blockchain functionality, such as those evidenced by Watanabe et al. (2019), pave the way for the application of NFTs in practical settings. Drawing upon the use cases outlined in Table 3, William Grant and Son's partnership with BlockBar for their aged whisky demonstrates how NFTs can assure customers of a product's provenance and authenticity (crucial elements in supporting SSCM claims). Similarly, Alfa Romeo's Tonale SUV was the first vehicle marketed with an NFT digital certificate, recording immutable service history data. Such an approach could extend to documenting a product's sustainability records. In short, NFTs can offer customers transparency and help verify sustainability credentials, thereby promoting informed purchases and incentivising sustainable consumption. Thus, it reduces information asymmetry and deepens the relationship between buyer and seller through increased trust. This is supported by Ying et al. (2023) who stress that retailers (or brands) need to share upstream supply chain data with consumers to fully realise the benefits of BCT.

P1. NFTs provide ownership of a digital receipt which can support and establish blockchain-verified SSCM certification and credentials and promote SSCM record keeping.

This proposition relates to SDG 12 (responsible production and consumption) and supports drivers for SSCM adoption acknowledged in the literature such as connecting SSCM practice with customers more clearly (Pagell and Wu, 2009; Ansari and Kant, 2017).

4.2. Incentivising and rewarding sustainable behaviour and consumption

Scholars such as De Giovanni (2022) have recently highlighted how companies can draw on theories like behavioural agency theory and offer blockchain-based incentives to customers and collectors to induce behaviours that support circular supply chains. Borrowing from the gamification literature helps further articulate an incentivising structure that drives and rewards sustainable purchases (and hence consumption) through NFTs. Gamification is the use of game mechanics (such as badges, avatars and leaderboards) in a non-gaming context to derive certain behaviours (Kark, 2011; Werbach, 2014). Such mechanics can be used in this context to incentivise and reward sustainable behaviour by devising a gamified engagement loop around the pursuit and consumption of sustainable items through the collection of rare NFTs (Zichermann and Linder, 2013). More precisely, this can be achieved through two main game mechanics: exclusive badges and avatars.

First, scarcity can be realised by attaching NFTs to sustainable purchases. This formulation guarantees that exclusivity is assimilated into what previously was a regular (physical) product. NFTs are one-of-a-kind and owning an exclusive and verifiable NFT in addition to the purchased product elevates the value of the purchased item to that of a rare collectible. Rare NFTs, therefore, can act as exclusive (shareable) badges, inculcating a sense of accomplishment and a social recognition incentive (Gazzaniga, 2010; Chou, 2021) by associating the desired behaviour (sustainable consumption) to different rewards (i.e. publicly-granted badges), motivating other consumers to follow a similar sustainable pattern to achieve the same social recognition.

Second, once the adoption of such mechanisms spreads through different suppliers and manufacturers within the supply chain, a centralised system, aggregating and visualising consumer NFTs and their contribution towards SSCM, can be a useful addition. This system can help consumers showcase all their purchases and provide a quantifiable representation of their contributions towards a sustainable ecosystem in the form of a visually appealing and customisable avatar (Hamari et al., 2014). This provides an opportunity for consumers to share and compare their contributions with others on different social media platforms. Again, this can help develop a positive competitive environment to that of a virtual leaderboard in terms of who owns which limited collectible and who is the most

sustainable. For example, those purchasing sustainable clothing lines can see their avatars don unique costumes, while those investing in organic food products can see their avatars display a healthy physique. This can develop a positive engagement loop of sustainable purchasing patterns from different and diverse supply chains.

Moving from the theoretical to the tangible, incentivising and rewarding behaviour is exemplified in several of the cases presented in Table 3. For example, after acquiring RTFKT in 2021 (Nike, 2021), Nike x RTFKT launched the 'Cryptokicks iRL' project as the first smart sneaker/native Web3 sneaker, offering an NFT-NFC (Near Field Communication) chip pairing for authentication. This case saw the introduction of the 'Cryptokicks iRL leaderboard', exhibiting a clear application of gamification techniques. This case exemplifies how integrating NFTs and gamification in physical product sales can potentially encourage consumer engagement with sustainable purchases. Furthermore, the NFTiffs by Tiffany & Co present new opportunities to sell exclusive merchandise to a select base of loyal customers, as they were made exclusively available to existing Cryptopunk NFT holders.

Other new modes of cultivating brand loyalty are exemplified in the use cases. For instance, Overpriced's strategy of allowing NFT holders ownership of a physical hoodie with limitless replacements. Offering a lifetime guarantee with the purchase of an NFT-linked product introduces a new secure standard in customer relations and retention where both brand and customers can be assured of authenticity. It incentivises quality manufacturing and the provision of repair services, promoting circularity. Importantly, this provides a novel model through which companies can servitise their existing product offerings. This approach is echoed in the Breitling luxury watch case study. Watch ownership is verified by an NFT-based Digital Product Passport (DPP), an emerging concept on the political agenda seen as pivotal for advancing the circular economy (Council of the European Union, 2020), which grants the holder access to exclusive brand events. This approach may support governments in making interventions which support more sustainable outcomes (tariff and subsidies), as outlined by Cao and Shen (2022). It is particularly significant in an era where the internet has reduced customer loyalty, given that customers can easily substitute products and services (Evans, 2017). Incidentally, the Overpriced case study also highlights the role NFTs may play in supply chain disintermediation, cutting out retailers and enabling Direct-to-Consumer supply chain models.

P2. NFTs can motivate customers willingness to purchase sustainable products by gamifying sustainable consumption and can build customer loyalty through servitisation models that extend buyer–seller relationships across time.

As with P1, P2 aligns with SDG 12 by using NFTs to gamify sustainable consumption, creating novel experiences that increase customer satisfaction, a known SSCM driver (Giannakis and Papadopoulos, 2016), thus potentially increasing their willingness to pay.

4.3. Incentivising and rewarding sustainable supply chains

A significant barrier to BCT integration is convincing all supply chain partners to participate (Kshetri, 2018; Saberi et al., 2019). The joint effort of supply chain partners is needed to create "win-win-win" situations where all parties (e.g. suppliers, retailers, customers) can be rewarded either financially or through other means for adopting sustainable behaviours (Li et al., 2022). The concepts of 'fractional NFT ownership' or 'NFT creator royalties' present relevant opportunities in this regard. Fractional ownership allows supply chain partners to own a share of an NFT (Ethereum, 2022). Focal brands may issue fractions of an NFT to partners who comply with sustainability standards, giving them a financial reward when the NFT is minted (sold). Furthermore, when an NFT is minted, a royalty percentage can be specified, ensuring the creator receives a cut of any future sales in secondary markets (Ibid). A practical example of this is Nike x RTFKT's 'Cryptokicks iRL' project, which set a 5 % royalty on future OpenSea sales (see Table 3). This approach could easily be extended to give all supply chain partners a cut of future royalties, promoting sustainable supply chain collaboration. Research by Tan (2022) supports this approach proposing that developers can take a cut of transactions on secondary

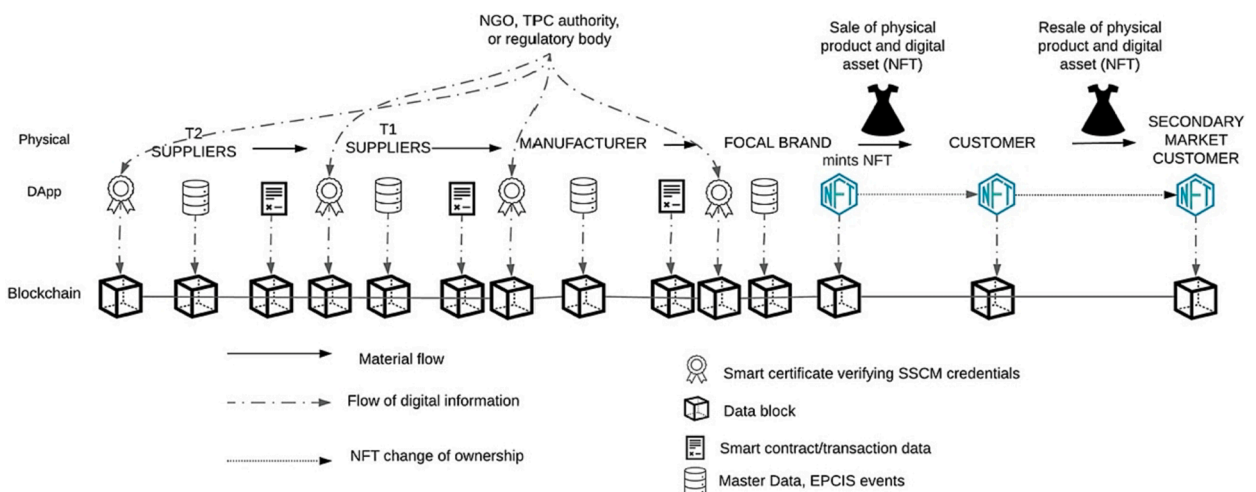


Fig. 4. Using NFTs on blockchain for SSCM verification and incentivisation (Authors' own).

markets, providing additional revenue streams. However, they warn that taking ‘too high’ a cut might discourage initial consumer purchases, negatively impacting overall profit. Interesting use cases have also emerged in the music industry that have implications for SSCM. For instance, BCT platform Opulous enables fans to invest in Music Fungible Tokens (MFTs) to support their favourite artists, gaining rewards as their artist’s music gains popularity (Opulous, 2023). This model could easily be copied by physical product companies, where consumers can support sustainable brands and products and potentially benefit from the company’s future success, reflecting a stakeholder-like relationship that rewards eco-conscious consumption.

Utilising NFTs in these ways incentivises the whole supply chain to compete together as a value chain. A visual hypothetical example of this is presented in Fig. 4, highlighting how various certificates and transaction data can be managed by blockchain smart contracts and sold as an NFT. Another solution would be for the tokens to be minted (created) upstream in the supply chain and then ‘written’ by supply chain partners as various transformations take place throughout the supply chain process (cf. dos Santos et al., 2021). Alternatively, each supply chain partner may mint an NFT that can be ‘collected’ by the customer.

P3. Leveraging NFTs (or semi-fungible tokens) through fractional ownership and creator royalty mechanisms incentivises the sustainable behaviour of all supply chain members.

P3 contributes to SDG 9 (industry, innovation and infrastructure) by promoting more sustainable supply chain infrastructure and directly supports the SDG 12 aim for sustainable production. Supplier involvement and incentivisation through rewards are acknowledged drivers for SSCM adoption (Giannakis and Papadopoulos, 2016).

4.4. Proof of ownership for anticounterfeit and circularity

The literature review revealed that BCT is a potential solution for addressing counterfeiting. BCT can help reduce information asymmetries that allow such practices to exist (Kouhizadeh, et al., 2021; Iyengar et al., 2023). Although there have been successful BCT pilots in luxury sectors e.g. DeBeers diamonds (Hargaden et al., 2019), research exploring BCT as a counterfeiting solution is still scarce (Toyoda et al., 2017; Danese et al., 2021). Danese et al. (2021) highlighted that the characteristics of BCT are not guaranteed to offer protection against counterfeiting and adulteration unless it is complemented by a suitable platform (DApp). Furthermore, there are challenges related to associating physical items with their digital records on the blockchain (discussed in Section 5.1).

NFTs help provide the missing piece of the puzzle for BCT as an anti-counterfeit solution. They can prove product custody for physical items as they move through the supply chain, providing complete assurance. NFTs offer a secure mechanism for asserting digital ownership, which addresses counterfeiting across various industries, including luxury wine and spirits, footwear, clothing, and fragrance. These NFTs enable the authentication of luxury commodities and foster trust in resales, as illustrated by the diverse cases presented in Table 3. For instance, in the luxury wine and spirits industry, initiatives by Cult Wines x Chateau Angélus, William Grant and Sons x BlockBar, and Patron use NFTs to provide product provenance authentication and verifiable ownership. In the footwear industry, Nike (RTFKT) ‘Cryptokicks iRL’ sneakers used NFTs linked with NFC tags for authentication. These use cases serve to partially address calls for more empirical evidence in this area (see Van Nguyen et al., 2023) and highlight the significant potential for NFT usage in secondary or rental markets where product authenticity is a major concern (Choi et al., 2020; Kansara, 2020). For example, if NFTs had existed in 2006, then it would be highly unlikely that Rudy Kurniawan would have been able to con auction house Acker Merrall & Condit into selling \$24.7 m of counterfeit vintage wine (Hellman, 2012). NFTs may be of interest for quality assurance policymakers, such as those involved with Protected Designation of Origin goods (European Commission, 2021).

P4. NFTs can reduce the negative sustainability impacts of counterfeiting by providing a robust mechanism for authenticating products and proving ownership, promoting trust in secondary markets.

P4 supports SDG 8 (decent work and economic growth) and environmental goals such as SDGs 13 and 15 (climate action and life on land respectively) by mitigating the negative environmental, social and economic impacts caused by counterfeiting. NFTs ensure credible product authentication, bolstering trust in secondary markets, resonating with SDG 12’s sustainable consumption goals, and furthering SDG 16 by fighting illicit trade, thus ensuring justice and building robust institutions.

The potential impact of NFTs on secondary or rental markets could accelerate the shift to a more Circular Economy (CE). The CE concept has emerged in parallel with the SSCM discourse (Genovese et al., 2017) and embodies a transition from the traditional linear economy to a more restorative system (Bressanelli et al., 2019). Digital technologies are aiding this transition and despite a 40 % revenue decline in the broader sector during the Covid-19 pandemic, luxury fashion saw growth in rental and resale markets, enabled by internet and mobile applications (Amed et al., 2021). However, counterfeiting risks threaten CE business models. NFTs, by mitigating these risks through secure authentication, provide the assurance needed to fuel luxury circular business model growth. This application of NFTs evidenced in many of the use cases presented in Table 3. For example, Alfa Romeo currently uses NFTs to authenticate service history to benefit resale value. It is well documented that BCT can provide product provenance assurances at the point of purchase. However, NFTs transform blockchain transaction history into a distinguishable asset for customers. This enables product tracking beyond the initial sale and provides comprehensive provenance for secondary users. Other identified use cases across industries, such as luxury apparel, premium wines and spirits, and collectible sneakers, concentrate on product authentication and verifiable ownership. Such cases highlight the potential of NFTs to bolster Digital Product Passports (DPP).

P5. NFT-authenticated products promote circular business models and supply chains by ensuring trust in rental, resale, and repair initiatives and associated concepts such as Digital Product Passports.

Effective inventory management is an acknowledged driver of SSCM (Koh et al., 2012). NFTs support circular supply chains in this

way and furthermore enable better asset management for customers post sale. This contributes to SDG 9 by fostering sustainable business model innovation within industries (rental and resale circular business models), to SDG 11 by reducing waste and improving resource efficiency aiding in the creations of more sustainable communities and cities, and to SDG 12 by ensuring sustainable production and consumption patterns through traceable resource cycles.

4.5. Reducing overproduction and overconsumption

Overconsumption and overproduction are intractable problems in many sectors (e.g. fashion and food) where vast quantities of excess stock negatively impact environmental sustainability issues such as carbon emissions and water consumption (Audet and Brisebois, 2019; Guo et al., 2020). From the case studies, we have identified a trend for a 'NFT first, physical product second' approach (see RTFKT, GAP, and Adidas examples in Table 3), offering the opportunity for companies to produce the exact quantity of products, eliminate waste and reduce operating costs. In innovation-led sectors such as luxury fashion, product flow to market typically requires agile supply chains (Fisher, 1997), where eliminating waste is not a prerequisite but still desirable. NFTs may help companies to implement agile supply chain strategies, achieve better cost efficiencies and reduce their negative environmental impact.

Issuing NFTs in advance of the physical delivery of goods may also influence supply chain management strategies that have traditionally been broadly characterised in terms of Make-to-Order (MTO) or Make-to-Stock (MTS) (Naylor et al., 1999; Soman et al., 2004). As NFTs provide a digital representation of physical products, the products themselves do not have to be MTS. In other words, there is no need to hold inventory prior to the sale of the NFT. NFTs may help innovate new supply chain production strategies whereby digital products are 'pushed' but the physical product is 'pulled' (with an MTO style execution) once the NFT has been minted. We propose the term 'Mint-to-Order' to describe this new production strategy for physical products in the metaverse age.

A Mint-to-Order strategy allows the decoupling point, the "point at which strategic stock is often held" (Naylor et al., 1999, p. 108), to be situated upstream, ensuring raw materials do not need to be committed until the NFT is minted. If an NFT does not get minted or sold, then the product will not be manufactured, presenting a risk-free way of trialling new products. There will of course be limits with regards to how long customers are willing to wait for physical items and supply chain responsiveness will be essential for NFT-based business models.

P6. A 'Mint-to-Order' approach (NFT first, physical product second) can help reduce the environmental waste and associated costs caused by overproduction.

A 'Mint-to-Order' NFT strategy aligns with SDG 12 by accurately aligning production with demand, reflecting lean production ideals through waste reduction (Das, 2018) and supporting the business case for more sustainable supply chain practices (Presely and Meade, 2018). For SDG 9, it embodies innovation in industry by integrating blockchain for more responsive manufacturing systems, as explored by Saberi et al. (2019). The model also touches on SDG 11 goals by potentially reducing urban waste and landfill dependency, supporting sustainable city solutions (Kaza et al., 2018).

The case studies indicate that NFTs are more than just a digital receipt or IOU. Consumers will likely be looking for NFTs that represent a digital twin to the real-world physical item that is an equally interesting value proposition within the metaverse space. For example, popular blockchain metaverses such as Decentraland already allow participants to buy NFTs of a 'virtual tunic' for their virtual characters to wear in the virtual world (Dowling, 2021). This concept is exemplified in the RTFKT case (see Table 3), where all NFT holders received 'airdropped' wearables for use in the Decentraland. Consequently, companies exploring NFT integration should consider the metaverse representation of their NFTs and how their digital operations support and complement physical supply chain strategies.

P7. NFTs that represent physical items need to represent an equally desirable value proposition in the metaverse.

Although having a parallel value offering in the metaverse does not initially align with SDG goals as clearly as other propositions put forward in this paper, it does futureproof the customer engagement aspect of SSCM (Pagell and Wu, 2009; Ashby et al., 2012) and can enhance customer satisfaction (Giannakis and Papadopoulos, 2016) of sustainable products by extending the value proposition into the digital realm. It touches on several SDG goals by increasing visibility of sustainable products and modes of production and consumption (SDG 12).

Although it has not been the focus of this paper, there is the potential for NFTs to replace physical products entirely in certain contexts. For example, take the Adidas use case in Table 3, physical products were only manufactured if the customer claimed it during the limited 'physical merch claim window', suggesting that some customers may only gain value from the digital twin of the product. This has important implications for mass market sectors e.g. fast fashion. For example, Dress X, a digital-only fashion company, founded to help address overproduction in the fashion industry, offers digital-only designs for a fraction of the cost of a physical item (DressX, 2023). Customers upload a photo of themselves to the application which then utilises augmented reality technology to fit the garment to the customer, ready for posting on social media.

Some early predictions have suggested that digital fashion could replace fast fashion or minimise the negative impact of fast-fashion supply chains (Roberts-Islam, 2021). NFTs are a natural extension of the digital product offering (Tong, 2021). In August 2021, Dress X launched its first ever NFT collection with Crypto.com, offering limited edition designs. This highlights how fast fashion brands may be able to offer semi-fungible digital alternatives to physical items without having to compromise on revenue. However, there may be negative unintended consequences (Carter et al., 2020) for social sustainability e.g. unemployment.

P8. NFTs can reduce the negative impacts of mass production by presenting a digital alternative to physical items.

NFTs have the potential to replace physical products in certain contexts, for instance as Virtual Reality (VR) or Augmented Reality (AR) clothing (e.g. Dress X). This may reduce the negative impacts of overproduction while preserving revenue - a critical shift aligning with SDG goals 9 and 12, supporting the business case for SSCM (Presley and Meade, 2018). The value of NFTs in digital realms could lead to waste prevention (the top priority in the waste hierarchy) ensuring less materials are committed to manufacturing (Defra, 2011).

4.6. Additional considerations for future research

A key aspect made apparent during this research was the lack of consensus about specific nuanced combinations of theory in such a novel and still emergent domain. Scholars such as Eslami et al. (2019) and Saberi et al. (2019) have advocated for the inclusion of technology in SSCM debates. Integrating theories that explain and evaluate how technology intersects with SSCM can prove beneficial as an expansion to the theoretical toolkit for SSCM and may help to understand the prevailing adoption barriers more effectively (Hwang et al., 2016; Saberi et al., 2019). Studies that explore supply chain innovation and technology adoption usually lack a strong theoretical framework for barrier evaluation and analysis (Kouhizadeh et al., 2021), yet there is no established consensus regarding an appropriate set of theories to apply to a broad question of adoption in this area. This is confirmed by Zhu et al. (2022) who recently published an article pointing to the atheoretical nature of the current corpus of literature discussing BCT in the supply chain context.

As a result, this paper has used the TOE framework to discuss how NFTs may address the barriers to BCT for SSCM. While the framework has been criticised for being overly generic (Zhu & Kraemer, 2005), this instance calls for a comprehensive framework that can assess a broadscale innovation. We do, however, acknowledge that the domain calls for a more comprehensive set of theoretical frameworks to assess such innovations, and believe that the TOE framework is a reasonable starting point for this endeavour. In their study of green supply chain adoption, Hwang et al. (2016) proposed a conceptual model, loaded with underpinning theoretical perspectives to the TOE framework to help strengthen its explanatory power. We build upon Hwang et al.'s work and propose some additional theoretical perspectives that could help strengthen the TOE framework for the purpose of NFT (or BCT more generally) for SSCM research (see Fig. 5). Firstly, following on from our study, we propose that the development of areas such as tokenisation and NFTs in the supply chain may require new theoretical perspectives from the world of gamification and behavioural theory to help

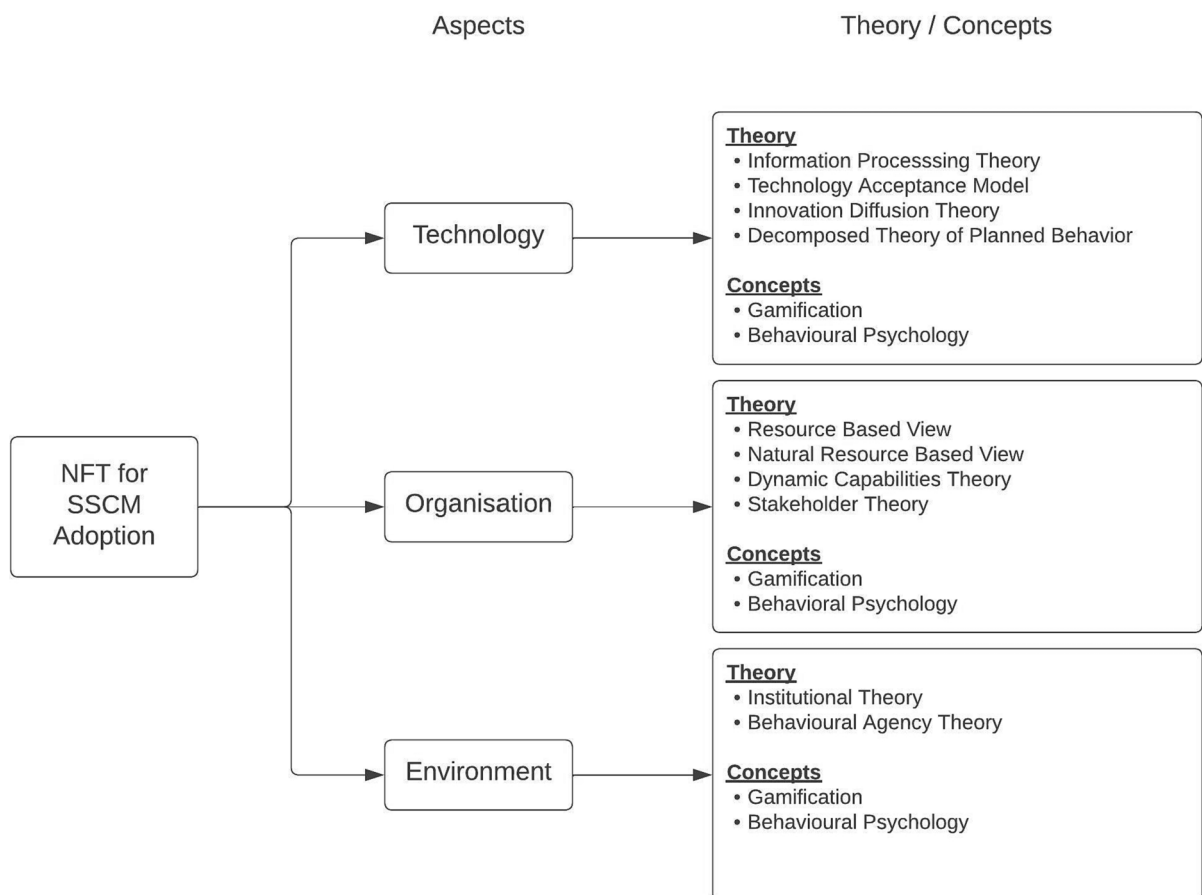


Fig. 5. TOE framework and underpinning theories and concepts suitable for future use in considering NFTs for SSCM adoption. adapted from Hwang et al., 2016

explain the motivations for adoption. Secondly, we propose future research should consider theories, such as Resource-Based View and Natural Resource-Based View, which can be useful for exploring organisational decision making - both are well-established in the field of OSCM and SSCM (Sarkis et al., 2011) and BCT (Treiblmaier, 2018). Finally, we propose the consideration of Information Processing Theory (IPT), another suitable theoretical perspective for understanding BCT-enabled supply chains (Saberli et al., 2019). We have summarised these potentially suitable theories and concepts in Fig. 5 as an acknowledgment that more work is needed to derive a more integrative set of coherent theories to supplement the TOE as the landscape for NFTs in SSCM matures. Considering the gamification concept and relevant aspects of behavioural psychology is key to the adoption of Blockchain-enabled NFT usage in SSCM. Evidence from the use cases to date suggests that future research could leverage the TOE framework as a base for the concurrent application of theory to understanding this novel area, effectively offsetting the shortcomings of the TOE and providing a solid foundation for exploring this emerging field.

5. Limitations of NFTs

Whilst NFTs can address some key BCT for SSCM adoption barriers, there are also some NFT-specific adoption barriers. These are discussed in the following sections.

5.1. Linking NFTs to physical items

Linking blockchain data to physical goods throughout a supply chain is a challenge for BCT to overcome (Watanabe et al., 2019; Klöckner et al., 2023). This is a particularly salient issue for NFTs. To date, this linkage has primarily been achieved using Radio Frequency Identification (RFID) barcodes and Quick Response (QR) codes that can be scanned to link to the blockchain data. However, barcodes are easily replicated (*Ibid*). NFC chips encrypted with unique data are a potential solution (Danese et al., 2021) and have been used in the Nike x RTFKT case (see Table 3). However, anything physically attached to the product could easily be removed and attached to counterfeit goods (Klöckner et al., 2023). NFTs do not solve this issue. For example, an NFT could be resold with a counterfeit good in place of the original physical item.

There are developments in the field of chemistry that can enable the link between physical items with the NFTs and the related blockchain data. Kennedy et al. (2017) created a chemical signature by embedding engineered nanomaterials into features of a 3D part that could be scanned via a smartphone camera; scans were uploaded as a blockchain entry on Ethereum. In the textile industry, FibreTrace has created a patented system which blends indestructible bio-luminescent pigment with fibres, creating a unique signature that can be scanned via a small portable device throughout the supply chain and the data uploaded to the Hyperledger blockchain (FibreTrace, 2021). This has been successfully piloted in the cotton and wool supply chain (Davies, 2022). Ellis et al. (2017) successfully developed a handheld Spatially Offset Raman Spectroscopy (SORS) device for detecting chemical components within whisky supply chains, enabling counterfeit alcohol to be analysed in situ. The 'Raman' data can be added to the blockchain with a network-enabled SORS device with networking capabilities. Fig. 6 presents a model for understanding how different layers of assurance can be achieved based on how the product is linked to blockchain data.

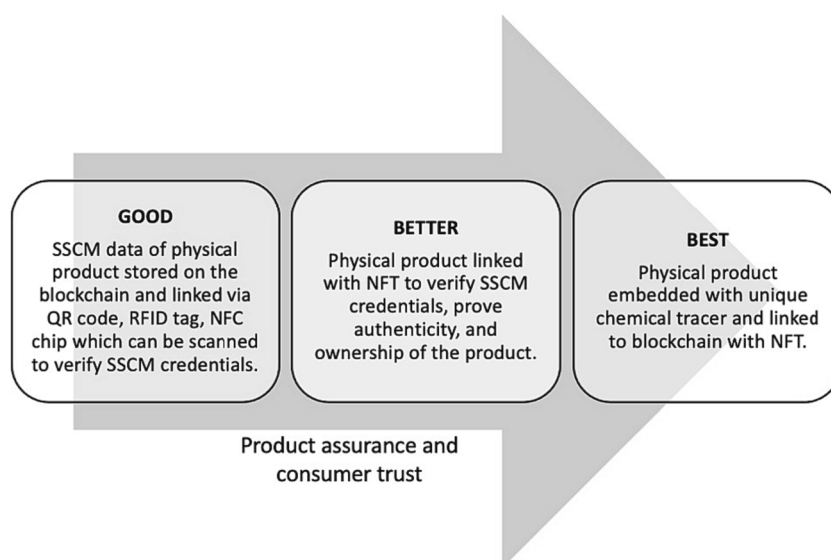


Fig. 6. Options for blockchain-enabled product assurance.

5.2. Interoperability

Many metaverse projects and NFT marketplaces are currently restricted to the BCT platforms on which they are built. This limits inter-metaverse asset (NFT) portability and the cross-platform buying and trading of NFTs (Wang et al., 2021). For instance, it is not possible for a customer to buy a pair of NFT sneakers in Wilder World and port them over to wear in Decentraland. Solutions are beginning to emerge, such as those from Art Labs, which specialises in offering cross-metaverse assets (Artlabs, 2023). However, selecting the right BCT platform is important as changing platforms is costly and can lead to managerial regret (Bai and Sarkis, 2020). The blockchain scalability trilemma should also be considered. For example, the EOSIO blockchain (see Table 2) has achieved impressive transaction speeds (exceeding those of Ethereum) but its decentralisation has been questioned (Zhou et al., 2020).

5.3. Minting costs

There are inefficiencies with the NFT minting process (Di Angelo and Salzer, 2020). Minting costs vary depending on the blockchain platform selected. On the Ethereum network, users minting an NFT need to pay a ‘gas fee’ which refers to the “unit that measures the amount of computational effort required to execute specific operations on the Ethereum network” (Ethereum, 2022). NFTs must be minted individually, a process that is time-consuming and requires significant computational power. Consequently, this can result in high and fluctuating gas fees (Regner et al., 2019). Additionally, buying NFTs requires purchasing the blockchain’s native cryptocurrency, creating further market volatility-related challenges (Ibid). Luxury supply chains with ‘innovative products’ and higher profit margins (Fisher, 1997) can better absorb minting costs than mass market ones.

5.4. Market risks

Crypto markets, such as NFT marketplaces, are vulnerable to speculative bubbles (Cheah and Fry, 2015). However, bubbles occur in many traditional asset classes and so this should not necessarily deter interested parties from investigating NFTs further. Reiterating DiAngelo and Salzer (2020), token value is dependent on the level of trust that the participating community has in it. Therefore, risks to corporate reputation when partnering with NFT marketplaces should be considered. NFT marketplaces are highly unregulated and not immune from corruption. In September 2021, OpenSea reported instances of insider trading. The NFT marketplace has since banned the practice (Hern, 2021). Recently there have been instances of fake NFT art sales, highlighting the importance of guaranteeing NFT authenticity (Bakare, 2021). This is a particularly salient point given the increased concern in luxury sectors following recent advances in generative AI and its ability to replicate signature luxury designs. This is exemplified by the high-profile battle between Hermès and artist Mason Rothschild surrounding the latter’s AI generated ‘MetaBirkin’ NFT sale. The judge ruled MetaBirkin infringed on Hermès’ trademark (McKinsey & Company, 2023). This case may encourage established brands to actively participate in NFTs as a means of authenticating and protecting their unique designs.

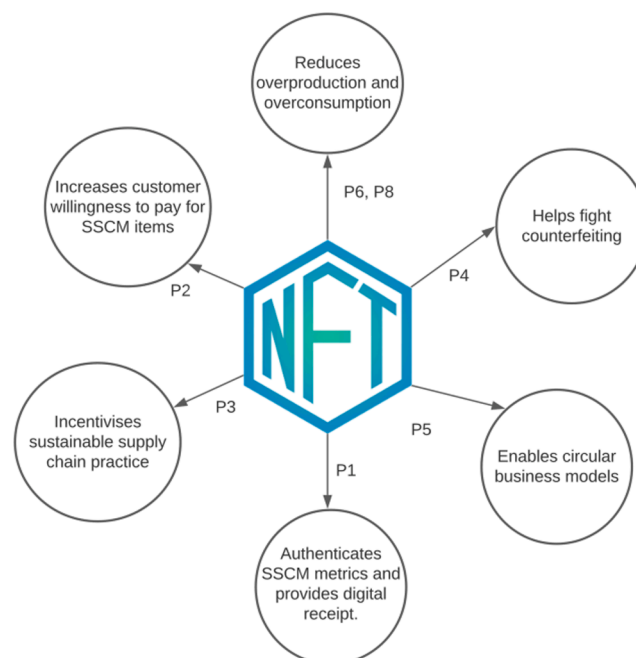


Fig. 7. Ways in which NFTs may drive SSCM.

6. Discussion

We have highlighted several ways in which NFTs can help improve SSCM practice and overcome the existing barriers to BCT adoption for SSCM. The ability of NFTs to provide ownership and create value helps businesses to present a clearer business case for BCT for SSCM. Fig. 7 presents a visual summary of the propositions that have been advanced, outlining the ways in which NFTs may positively impact SSCM and strengthen the business case for BCT for SSCM.

Table 4 is based on the TOE framework that was used to introduce the barriers to BCT for SSCM (Section 2.2). It summarises how NFTs may (or may not) impact each barrier. NFTs are bound by many of the same technological constraints as BCT and so do not help to address technological barriers (although may help to improve the perception of BCT). However, they show significant potential for addressing some of the key organisational and external environmental barriers to BCT for SSCM adoption. NFTs provide an opportunity for blockchain-based SSCM product data to be presented in a way which represents a clear and meaningful value proposition for customers.

Table 4
How NFTs address BCT for SSCM adoption barriers ().

	Barriers to BCT for SSCM	Can NFTs help?	Comments
Technological context (T)	T1 - Security	No	NFTs are a layer on top of a blockchain and are only as secure on the blockchains on which they exist.
	T2 - Access	No	NFTs are unlikely to overcome the barriers relating to the compatibility of BCT with existing supply chain information technology systems.
	T3 - Negative perceptions	Potentially	Only if they represent a trusted value proposition to stakeholders (e.g. consumers) but NFTs are still open to corruption and may not dispel potentially negative connotations of BCT and cryptocurrencies.
	T4 - Immutability	No	Once you mint an NFT you cannot change its contents. Therefore, NFTs do not solve the immutability challenge of BCT.
	T5 - Immaturity	No	NFTs do not solve the blockchain scalability trilemma.
Organisational context (O)	O1 - Financial constraints	Yes	Helps to justify investing in supply chain sustainability by supporting the business case.
	O2 - Lack of managerial commitment	Yes	Helps managers to develop a clear business case for BCT for SSCM.
	O3 - Lack of organisational policies	Yes	Helps companies understand the applicability of BCT for SSCM.
	O4 - Lack of knowledge and expertise	No	Could add further complexity. However, it could help engage managers/employees to gain knowledge about the technology.
	O5 - Organisational culture	Potentially	Could be the catalyst to engage employees with BCT for SSCM.
	O6 - Inertia	Potentially	There are many blockchains emerging which support NFTs presenting managers with an overwhelming array of potential platforms and may lead to a reluctance to commit.
	O7 - Lack of benchmarks	Yes	Could facilitate the development of appropriate standards (e.g. for counterfeiting).
Environmental context (E)	E1 - Lack of customer motivation to adopt BCT and make sustainable purchases	Yes	Activates customer core drivers for purchase, therefore, increases customer willingness to pay for authenticated SSCM products and services.
	E2 - Lack of supply chain alignment	Yes	NFTs encourage the whole value chain to collaborate and compete as one. NFTs also help prove the chain of custody throughout the supply chain.
	E3 - Information disclosure between supply chain partners	No	Not directly. However, supply chain partners may be more incentivised to disclose information due to the benefits that can be gained from collaborating with supply chain partners.
	E4 - Integrating BCT and SSCM	No	Not directly. However, they could help extend the effectiveness of existing supply chain technologies such as Radio Frequency Identification (RFID).
	E5 - Cultural differences of supply chain partners	No	Not directly. Although they may help unify international supply chain partners with a common goal.
	E6 - Lack of governmental policies	Yes	NFTs can incentivise government to introduce NFT policies that address counterfeit supply chains.
	E7 - Market competition and uncertainty	Yes	NFTs represent a clear value proposition to customers. Also, the 'NFT first, physical product second' approach can minimise risks related to market uncertainty.
	E8 - Lack of external stakeholder involvement	Yes	Could engage NGOs, third-party authentication bodies to encourage adoption. SSCM certification can be issued as NFT.
	E9 - Lack of industry BCT standards	No	NFTs do not solve this and may add further complexity that prevents the development of industry standards.
	E10 - Lack of rewards and incentives	Yes	NFTs can help to incentivise and reward consumers for sustainable consumption and incentivise supply chain partners to engage in SSCM practices.

adapted from Kouhizadeh, et al., 2021

6.1. Implications for adoption

Digital MTS, physical MTO ('Mint-to-Order') – A potential application with far stretching implications for SSCM is the concept of having a digital make-to-stock process running concurrently with a physical make-to-order process. This decoupling of value allows the consumer to start deriving value from the purchase immediately before the delivery of the physical product. Ownership is conferred upfront, and thus value from this ownership can start to be derived in the digital realm (metaverse). We are proposing the term 'Mint-to-Order' as a term for this production strategy for the metaverse era, depicted in Fig. 8. This promotes a production strategy whereby organisations only make what they mint having significant implications for waste reduction.

Seamless transition between digital and physical worlds (Metaverse) – Organisations need to think simultaneously about their value propositions in the real world, and also the metaverse. While in their most primitive form NFTs can act as a digital receipt and an authenticator, it is likely that the most successful initiatives will be those organisations which concurrently provide products that are equally desirable in the metaverse (as NFTs) as they are in their physical form, in real life. The case studies that we have examined show early signs of this effect and its ultimate potential. A simple illustration for understanding the linkage of the metaverse with the physical supply chains via a BCT interface is depicted in Fig. 9.

Gamification – The inherent malleability of a digital realm means that digital NFT-minted products are more amenable to gamification than their physical counterparts alone. This, and the examples we have presented in this paper, suggest that gamification will be an increasingly leveraged capability for organisations looking to create value from their sustainable supply chain practices.

Shifting organisational structure – The nature of NFTs allows for organisations to leverage SCM practice into meaningful value propositions to customers. The example here would be of showcasing the ethical and sustainable sourcing of a product's long-tail supply chain. This is likely to require the formation of new business functions at the intersections of digital marketing and supply chain management.

Authentication Verification – The most adopted use-case for NFT will continue to be the immediate benefits to verification and authentication conveyed by the technology. As has been highlighted, this has important implications for anti-counterfeiting methods.

Not all industries are equally suitable at present – Although NFTs have the potential to enjoy widespread adoption across multiple industries and market sectors in the longer-term, this research suggests that, initially, their application may be better suited to sectors and industries where scarcity, rarity, exclusivity and uniqueness (the characteristics of NFTs) are desirable qualities and where companies are not competing on cost. The luxury sector is an example of this. Luxury is a macroeconomic sector which encompasses many different industries, including automotive, apparel, leather goods, jewellery, watches, beauty and fragrance, yachts, and fine foods (Nowiński and Kozma, 2017; Saberi et al., 2019). Some scholars have already highlighted that BCT application is particularly

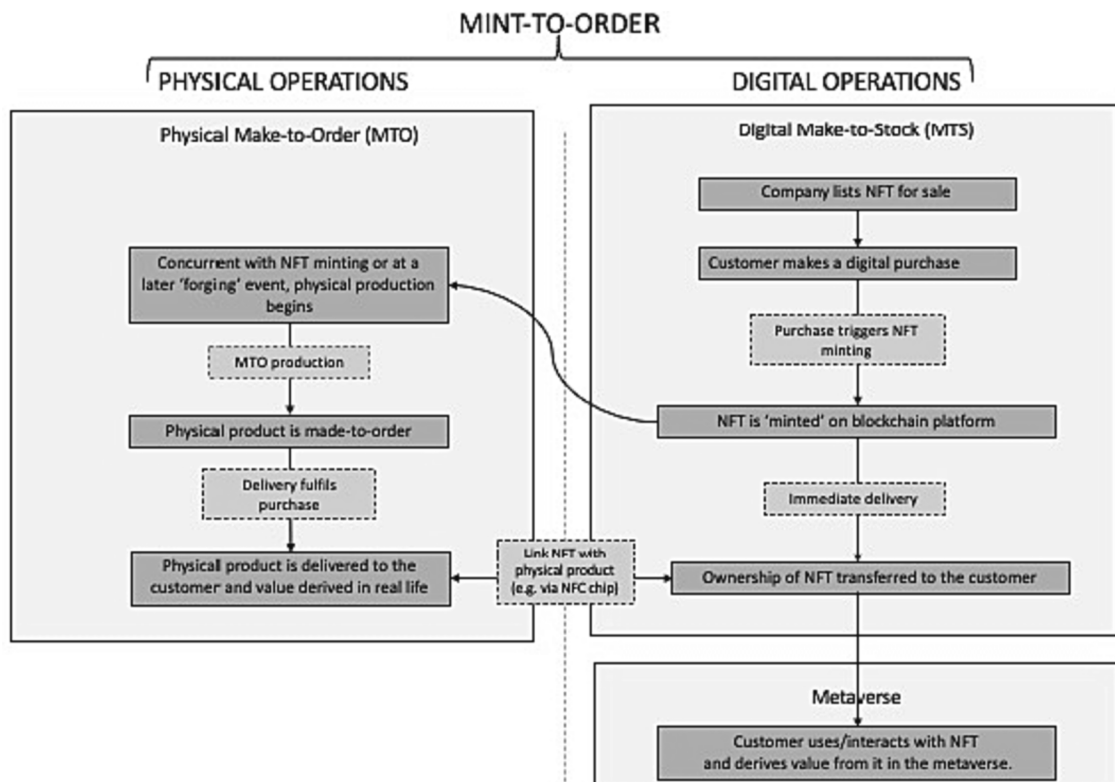


Fig. 8. 'Mint-to-Order': a production strategy for the metaverse age.

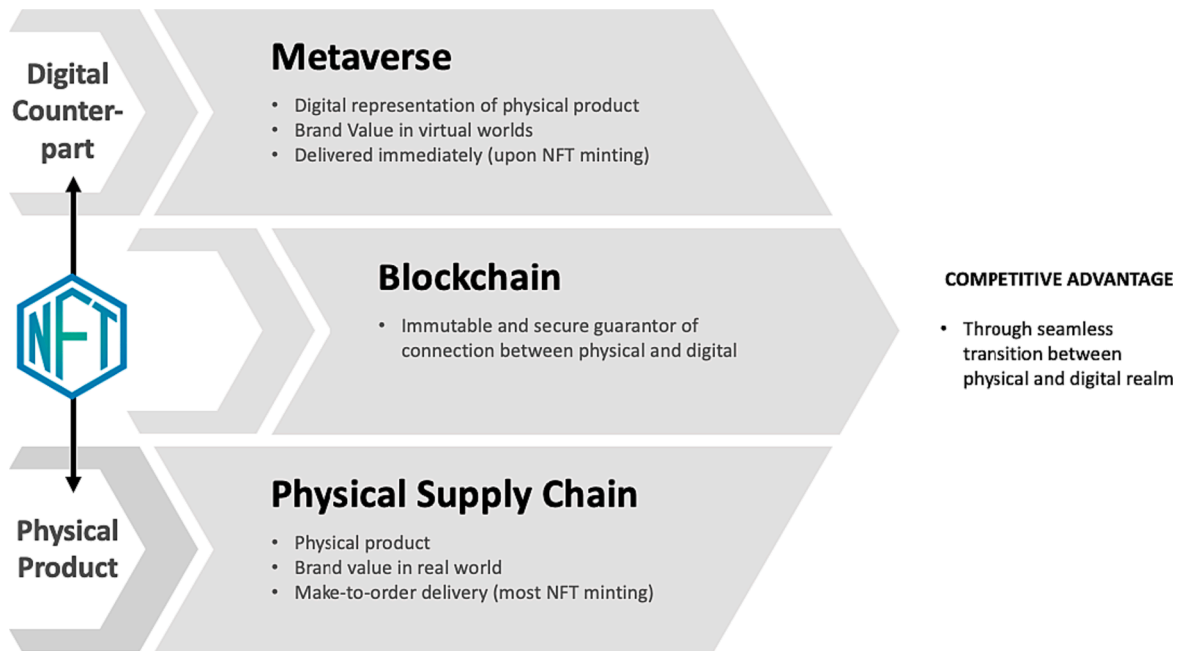


Fig. 9. NFT value proposition.

suitable for usage in luxury supply chains (Nowiński and Kozma, 2017; Saberi et al., 2019; Wang et al., 2019; Danese, et al., 2021). Research by Feng et al. (2020) suggests luxury brands can receive negative stock market reactions to sustainability announcements, due to a shareholder-perceived identity mismatch between luxury and sustainability. The study found that negative effects had diminished in recent years, suggesting a wider acceptance of the sustainability agenda in luxury supply chains. This supports recent reports which suggest luxury fashion customers are beginning to demand much more in terms of supply chain transparency and sustainability (Amed et al., 2021). However, we recommend that luxury brand managers should carefully consider the customer messaging associated with NFT implementation announcements, ensuring that the rationale for NFT implementation aligns with brand identity.

7. Conclusions

This paper extends the existing BCT for SSCM literature by conceptually exploring NFTs, a recent technological development in BCT. We conclude that NFTs have the potential to be the elusive BCT ingredient for supporting sustainable supply chains. The ability of NFTs to prove ownership of unique digital and physical assets adds valuable and previously absent BCT capabilities. NFTs can help a wide range of stakeholders understand the value and benefits of BCT. We have highlighted several ways in which they can strengthen the business case for BCT for SSCM, helping to overcome some of the major adoption barriers. We conclude that NFTs show significant potential for advancing anti-counterfeiting BCT solutions and reducing the associated negative sustainability impacts. NFTs exhibit significant promise for supporting circular business models related to secondary markets and the sharing economy. One of the key contributions of this paper is the proposition of a novel and more sustainable 'Mint-to-Order' production strategy for the metaverse age, combining a digital MTS with a physical MTO strategy.

This paper has highlighted some NFT-specific adoption barriers. However, NFTs are bound by many of the same technical challenges as BCT. If the blockchain scalability trilemma can be overcome, then NFTs will become extremely scalable (Entriken et al., 2018; Regner et al., 2019) and could enjoy widespread adoption for SSCM. While NFTs and BCT offer potential for SSCM, their intense energy consumption poses a sustainability concern. Negative environmental impacts could undermine the SSCM benefits that NFTs bring. Therefore, pursuing energy efficient NFTs and BCT solutions is crucial to the application of the technology in this context. It is also worth noting that while the focus of this paper has been on blockchain-based NFTs, developments in the broader domain of distributed ledger technologies such as IoT DAG platforms (e.g. IOTA), which do not currently support NFTs, are ongoing. As the technology landscape evolves, it is anticipated that more sustainable (energy efficient), scalable, and cheaper platforms (zero gas fees), like IOTA, will likely soon support NFTs, broadening their application in SSCM (IOTA, 2023).

This paper has proposed that NFTs may be more suited to luxury markets initially. However, if BCT and NFTs become more scalable and affordable then application will likely extend to mass market products. For example, semi-fungible tokenisation could have important implications for pharmaceutical supply chains that are vulnerable to corruption and counterfeiting. This paper has proposed several avenues for future research and advocates for empirical research to broaden and deepen our understanding of how NFTs may be utilised effectively for SSCM.

CRedit authorship contribution statement

Jennifer Davies: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing, Visualization, Formal analysis. **Hossein Sharifi:** Methodology, Supervision, Writing – review & editing, Conceptualization, Project administration. **Andrew Lyons:** Methodology, Supervision, Writing – review & editing, Conceptualization. **Rick Forster:** Conceptualization, Investigation, Methodology, Visualization, Writing – original draft. **Omar Khaled Shokry Mohamed Elsayed:** Conceptualization, Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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