Plastic Credit: A Consortium Blockchain-based Plastic Recyclability System

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Abstract. By the end of 2015, approximately 6300 million tons (Mt) of plastic waste had been generated globally, but less than 10% of plastics was recycled (Geyer et al., 2017). Since different types of plastics have various degrees of recyclability, consumer information about plastic product recyclability is paramount in order to increase the levels of plastic recycled. Against this context, the objective of this work is to define a plastic credit system to increase the amount of recyclable plastics. The plastic credit system assigns credit information to each plastic product and its corresponding company based on the percentage recyclability value of the plastic type and its composition. The methodology proposed is based on a unified and transparent credit system established by a double-chain system, which comprises a public blockchain CreditChain and a consortium blockchain M-InfoChain. The results show through the overall system performance analysis that the designed plastic credit system is capable of promoting a demand shift towards plastic products with higher plastic recyclability and achieving a lightweight operation for resource requirements and system maintenance.

Keywords: Plastic waste, consortium blockchain, demand shift, consensus coordination.

1. Introduction

The dramatic increase in global plastic pollution is highly worrying for citizens worldwide who are concerned about the environment and economic sustainability (Deviatkin et al., 2019). Plastic waste has become one of the most formidable environmental problems of our age, and solving it without increasing other environmental burdens will require approaches that tackle wider concerns around the unsustainable use of resources (Zheng et al., 2005; Ayeleru et al., 2020). Dealing with plastic waste is expensive and requires collection, preprocessing, recycling, etc. (Siddique et al., 2008; Rochman et al., 2013). Current waste management methods, including recycling (Dodbiba et al., 2008), incineration (Rajendran et al., 2013), and landfill (Hopewell et al., 2009) for plastic waste types such as PE, PET, HDPE, PVC, etc. are already being analyzed using Life Cycle Assessment (LCA) and various economic assessments (Verghese and Grant, 2005; Bernardo et al., 2016; Antelava et al., 2019; Deviatkin et al., 2019; Bahij et al., 2020). However, at present, recycling technologies and waste management systems do not yet record the impacts due to the amounts of plastic waste being generated (Fletcher and Mackay, 1996).

Encouraging customers to reduce single use plastic consumption and motivating plastic producers to produce more recyclable plastics are essential to the health of the global environment, especially marine life (Van Rensburg et al., 2020). However, purely relying on conventional approaches and technologies for handling plastic waste is not effective in eliminating hazardous plastic waste in the environment (Horodytska et al., 2019). Important to our study is the fact that more than 20 different recycling labels for plastic alone exist in the market, and customers are confused about which plastic products are recyclable and which products are actually recycled (Whitman and Begin, 2017; Rackovan et al., 2018; Tomlinson, 2019). The information provided to customers is often unclear, leading to reported confusion and mistrust where there is lack of standardization and accountability with individual brands that create their own labels and claims without third party certification (Aschehoug et al., 2013). Rising public awareness and concern about plastics has prodded organizations and companies to clearly communicate their packaging information, given that clear plastics labelling is a powerful way to help consumers buy more recyclable and recycled products and to dispose of them correctly (Faraca et al., 2019). By so doing, consumers would benefit from a unified system for measuring the real value of plastic products in terms of its recyclability in order for “the good quality plastic product to drive out the bad” (Rolnick and Weber, 1986). To address the problem of ambiguous plastic labeling, this paper proposes a credit system based on the quality of the plastic. From the outset, however, this study finds that the main challenge behind the credit system is the engendering of trust between customers and plastic product manufacturers, and among plastic producers and manufacturers of goods which use plastic, where neither verification of actual plastic usage nor credit authenticity in this process can yet take place. A transparent and secure platform for generating and checking credit information is therefore essential in the plastic management system.

At present, most credit systems nevertheless rely on a centralized infrastructure and imply the involvement of a trusted third party (Dongyu et al., 2012). For example, UK packaging regulations require businesses to finance the recycling of plastics by purchasing recycling evidence notes (PRN) (Bailey et al., 2004). Large companies or organizations need to be responsible for the plastics they make, use, or sell, and the note is issued by a third accredited party, a reprocessor, as evidence of the receipt of a certain tonnage of packaging waste. However, such a centralized system generally has significant drawbacks, such as a crisis of trust caused by recycling information asymmetry and information that can be tampered with easily. Decentralization can solve this problem by providing an immutable record within a trusted environment. Blockchain provides the equitable management of credit information and interface for the public to check on a secure distributed ledger book (Ølnes et al., 2017). Decentralization in blockchain offers new structures for collaboration and technological solutions where people take accountability for the credit that is shared among large groups of people (Treleaven et al., 2017). Thus, blockchain-based plastic credit leverages the following aspects of blockchain technology by:

(1) Eliminating a trusted intermediary and building trust among stakeholders.

(2) Providing immutable records of credit generation from plastic producers/manufacturers and transparent credit history for customers to check.

(3) Having a lightweight infrastructure capable of accommodating the plastic production and plastic waste management industry.

In this context, we propose a blockchain-based PlasticChain for managing the plastic credit for plastic products/companies. In a PlasticChain system customers are able to retrieve credit information as a reference before choosing a product. Plastic producers and product manufacturers can publish means of production contracts and plastic production information to form a self-regulated body that can check the information's validity. In fact, it is expected that, with the increasing number of public users participating in managing the plastic waste, there will be large-scale enquiry requests. However, plastic producers and product manufacturers require a fair and transparent platform to continuously audit plastic production's recyclability and quantity (Laurent et al., 2014). Therefore, this system includes a public sub-blockchain for interfacing with customers where a consortium sub-blockchain is adopted in the community of producers and manufacturers. The main contributions of this paper can be summarized as follows:

(1) A blockchain-based plastic credit management system is proposed to provide a unified and trustworthy credit system for evaluating plastic product recyclability for customers (plastic product buyers and used plastic buyers) to check credit information

and aid the purchasing decisions.

(2) By introducing the potential of the market, consumers can benefit from the PlasticChain system by verifying the recyclability of plastic products and encouraging the sale and production of recyclable plastics.

(3) PlasticChain separates the public user interface from intra-production users who can efficiently reduce communication overhead and computation costs with an increasing number of public users.

(4) By proposing Practical Byzantine Fault Tolerance (PBFT)-based consensus coordination process on M-InfoChain, plastic production information can be checked and audited by all consortium members to ensure the record validity and authenticity.

The paper is organized as follows. In Section 3, the system model for the blockchain-enabled plastic credit management system is presented. In Section 4, the details of the proposed plastic credit scheme are described. Thereafter, the system economic impact and performance evaluation are presented in Section 5, and conclusions round out the paper in Section 6.

2. Theoretical background discussion

The theoretical background for the plastic credit system design will be discussed from two aspects. The first subsection covers current waste management methods with different economic instruments. The second subsection presents the blockchain infrastructure design choices for different applications.

2.1 Waste Management Methods

In order to promote waste prevention, government and local authorities have also proposed economic instruments, including taxes, fees and charges, Deposit-Refund Systems (DRS), subsidies, a tradable permit system, and so on (Hogg et al., 2011). These instruments use different economic models to stimulate municipal waste prevention and improve resource efficiency. A general waste prevention summary for each instrument with its corresponding economic model is shown in the Table 1.

Economic Instrument Type	Features	Limitations	Product examples	Application cases/projects
Taxes, Fees and Charges (Walker et al., 2020)	• Levied to the cost associated with the provision of a service • Low compliance cost	• Requires highly formulated taxes for the market • Unfair competition and additional burdens on companies	• Disposal Tax • Packaging Tax • Variable VAT Charge • …	DVR charging in the Netherlands (Van Beukering et al., 2009)
Deposit-Refund Systems (Suter et al., 2019)	• Encourage the return of the materials • Increase the use of refillables and avoid harmful chemicals being mobilized	• Lack of a strong waste prevention component to DRS • The system could only focus on the return of recyclable items	• Beverage Containers • Products (e.g. tires)	Metal Beverage Can Return (D Hogg et al., 2011)
Subsides (Allison et al., 2020)	Encourage behavior change at the household level	• It requires extensive behavior change campaigns • Non-standard subsides resources for different communities	• Home composting schemes • Waste prevention subsidies • Loyalty card scheme • …	Food Waste Composting (M Farrell et al., 2010)
Tradable Permit System (Peake et al., 2020)	Provide flexibility to all local authorities with responsibility for waste	• It is hard to track the permit fund usage • Higher Compliance cost than for taxes	• Disposal • Packaging	UK's Packaging Recovery Note System (Bailey et

disposal	al., 2004)

According to Hogg et al. (2011), in general, the evidence of prevention effects is strongest for product taxes when we think of economic impacts at national level. Furthermore, the use case in the UK of Packaging Recovery Note System (PRNs) enhances the flexibility for local authorities and organizations to participate in the waste prevention process, where it brings responsible companies and consumers into the game. However, there are limitations for the PRN system; for example, the customer cannot verify if the product is recyclable, or their company could just buy the recovery notes without using the actual recyclable contents. There is mistrust between plastic companies and customers on the type and recyclability of plastic products and whether such products will be recycled. In the aim to reduce the mistrust and confusion between customers and companies, this paper designs a plastic credit system in order to improve the plastic quality.

2.2 Blockchain infrastructure design choices

Blockchain is a shared and trusted distributed ledger technology that permits the recording of any digital asset transaction between parties over a decentralized, encrypted network, which is initially developed as a mechanism to record financial transactions (Liu et al., 2018). There are three main types of blockchain that correspond to participation method: public, consortium and private blockchains (Jiang et al., 2018).

In the public blockchain, participants are allowed to take part anonymously, and access the network and blockchain without permission. The transactions on the blockchain are available for checking, and all peers are allowed to make transactions (Jaag et al., 2017). In the consortium blockchain, access and update operations are only allowed for members of the consortium. Only the selected set of nodes are responsible for validating the blockchain in the network (Marc et al., 2016). The private blockchain is applied in private organizations for database management and auditing (Gramoli et al., 2020).

In considering the public access requirement from the plastic users, operation efficiency and confidentiality between manufacturers and producers, this paper adapts a hybrid blockchain infrastructure to accommodate all requirements. With reference to the model proposed in (Xu J et al., 2019), such infrastructure ensures the data privacy while supporting fast and secure public access for industrial level applications.

3. System model

In this section the system model for the blockchain-enabled plastic credit management system PlasticChain is presented.

3.1 Model description

PlasticChain is a plastic product-based blockchain system in which products containing raw plastic are produced by private sector plastic manufacturers. The label on the plastic product gives the plastic credit information, and may also contain the plastic type and composition (given on a voluntary basis). Users are able to collect the plastic information from the label and verify its authenticity on PlasticChain. The plastic products are labelled by manufacturers where the corresponding factory or company is responsible for providing the correct information to customers. The information is distributed in an off-chain manner so that it is not directly involved in the blockchain. As illustrated in Fig. 1, PlasticChain can be divided into several different components described as follows:

(1) CreditChain: is a public blockchain for storing the plastic credit information for registered plastic products and companies. It is a permission-less blockchain that allows anyone to read information and mine it at any time. CreditChain is composed of a series of *CBlocks*, and it expands continuously with more user nodes on board. Each *CBlock* contains the information of the credit check and encapsulates user activities.

(2) M-InfoChain: is a consortium blockchain for storing manufacturers' document contracts and production information. Consortium members, the registered producers and manufacturers, need to publish their means of production, which are then added as a transaction by the consortium members appending to the M-InfoChain. At each timeframe, manufacturer nodes select a leader for aggregating valid transactions and generating new blocks (*MBlock*) on M-InfoChain. Some events, such as production line upgrade or change of product design, will result in credit updates on M-InfoChain, and will call the contract to update information on CreditChain by M_i.

(3) Producer Nodes: A producer node (P_i) is a company that produces raw plastic material, e.g., plastic bags, films, and bottles. Products from producer nodes may consist of various types of plastic such as PET, PP, HDPE, etc., all of which have different degrees of recyclability. All raw plastic material from producer nodes needs to be registered and verified by uploading their production contract codes to the M-InfoChain. The production contract codes contain formula and composition documents based on their production lines, where credit is then calculated by the plastic type and quantity. It then needs to be checked and verified by consortium members via consensus coordination in order to be valid for production. Consortium members must

continuously provide production information for credit updating.

(4) Manufacturer Nodes: A manufacturer node (M_i) is a company that purchases raw plastic material from producer (P_i) to contain or package their product, e.g., shampoo, juice, milk. An example could be Innocent, which sells drinks in plastic containers (Wikipedia, 2020). The product credit value is calculated based on the raw plastic material credit information from M-InfoChain. Thus, the manufacturer and producer nodes form a consortium blockchain where their behavior is restricted by the rules of the consortium. Each of the manufacture production logs needs to be verified by submitting the factory production history logs to the consortium network.

(5) User Nodes: An ordinary customer can be viewed as a user node (U_i) in PlasticChain. The user node can enquire about the plastic credit information from the PlasticChain by aggregating and encrypting data from plastic products. The lightweight user nodes will only download the block headers from CreditChain as mobile miners. The credit information from CreditChain will supplement the credit check for plastic credits, but at the same time lightweight user nodes cannot generate, publish, or verify credit information.

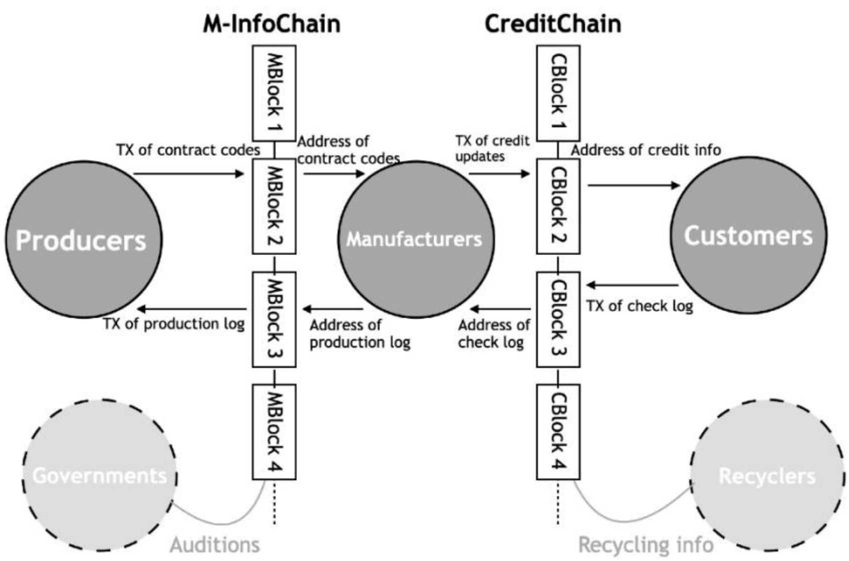

Fig. 1. System model of PlasticChain.

As illustrated in Fig. 1, each node in the PlasticChain is connected to the chain with the data flow. User nodes read plastic information from plastic product labels in order to check the product information from CreditChain. User nodes U_i encapsulate read operation into a transaction and sends to the CreditChain, where the check history is also recorded on-chain. M_i and P_i encrypts the document for means of production and sends the encrypted transaction in the form of contract address to the M-InfoChain. The transaction generated from the M_i node calls the plastic credit scheme to output the credit score and update to the CreditChain periodically, or on event triggers.

In addition, government and recyclers can also join PlasticChain. Recyclers are plastic waste collectors/management companies with Know Your Customer (KYC) on CreditChain, and who are capable of writing transactions. And so, recyclers can provide more accurate credit information by providing plastic feedback from the society. Both government and recycler nodes are optional for this system, but they are envisioned for future integration. The government node can play the role of auditor, which is formulated by government or regulatory bodies of the environment sector and can verify the validity of manufacturer document contracts and production information at any time by joining the consortium network on M-InfoChain. Furthermore, the government node could suspend or terminate producer or manufacturer nodes in the case of fraudulent or illegal actions.

3.2 Design principles

In a distributed system with the integration of public and consortium blockchains, the infrastructure should be efficient, accountable, and confidential (Onik et al., 2018). To achieve a reliable plastic credit system, the infrastructure design should uphold the following principles:

(1) *Efficiency:* The system should be able to support large volumes of user enquiries and check histories in a low latency and high throughput manner. In the Paxos-based or Byzantine Fault Tolerance (BFT) consensus mechanism, the performance of the network will decrease as the number of nodes increases, thus affecting the user experience in a plastic credit search.

(2) *Accountability:* In order to prevent fraudulent and unfaithful disputes in plastic production, the consortium network in M-InfoChain must be responsible for publishing production contracts and information; it should also able to manage and withstand malicious attacks. Government and regulatory sectors are allowed to audit the means of production to ensure accountability of the credit system.

(3) *Transparency:* M-InfoChain provides a consortium community among plastic producers and manufacturers, where the plastic production is continuously monitored and checked by consortium members, thus forming a self-regulated body with transparent production histories. CreditChain also provides a window for the public to inspect and audit the plastic manufacture and usage, where credit information is stored and shared in a transparent and untampered manner.

4. PlasticChain scheme

A description of the PlasticChain scheme includes types of transactions in PlasticChain, block design, and consensus process coordination.

4.1 Overall description

PlasticChain is a blockchain for manufacturers and producers to publish their means of production for the purpose of credit rating, and for public users to check the credit of a product or company. It consists of two sub-chains for achieving the functionality, known as, respectively, CreditChain and M-InfoChain.

The implementation of the PlasticChain scheme is based on data collection interface with manufacturer and producer nodes, M_i, P_i, and user nodes, U_i. The application interface provides means of production contract generation, plastic product manufacture information, and credit search. Contracts or checking histories are then encapsulated as transactions writing on blockchains, where consensus mechanisms in its corresponding sub-chain will check and verify to generate a new block. The information in the transaction is stored in a Merkle tree, and the header contains the hash of previous blocks, index, timestamp, nonce, etc. The smart contract on M-InfoChain calls the credit update to send information to CreditChain, where the data is next transmitted in the P2P network. And U_i on CreditChain updates the credit information by broadcasting it to the network peers. The workflow is depicted in Fig. 2.

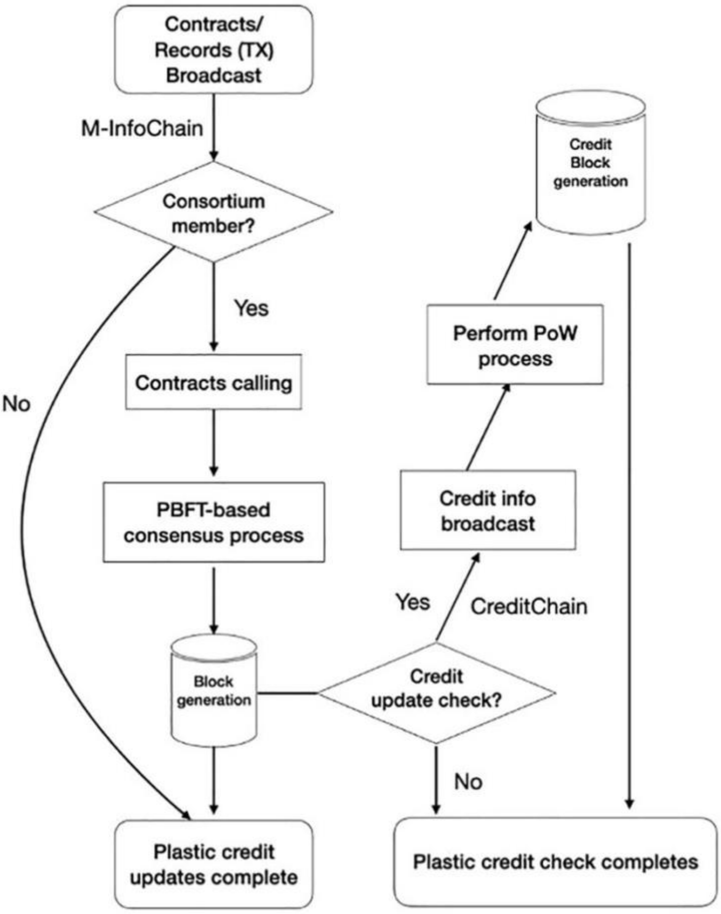

Fig. 2. System model of PlasticChain.

4.2 Transaction and block structures

All activities are written on the blockchain as transactions. By aggregating transactions, it generates a candidate block for the consensus layer to select. In order to interact with multiple stakeholders, there are two types of blocks on sub-chains, identified as, respectively, *MBlock* and *CBlock*. According to the transaction (TX) types, each type of block contains two different types of the transaction, depending on the action performed by participants.

(1) *Transaction structure:* contains information about the operation from the node in the network. The transaction format can be represented as follows:

$$TX_{i,j} = \left\{ H_{i,j}, version, ID_{i,j}, TS_{i,j}, I/O_{i,j} \right\} \tag{1}$$

$U_{i,j}$, $M_{i,j}$ or $P_{i,j}$ generates $TX_{i,j}$ to transmit their demands information to the sub-chains, where *i* and *j* are the identifiers for, respectively, the node and the raw plastic/plastic product. $H_{i,j}$ is the hash value for the transaction, and *version* is the version number of the transaction in correspondence with its sub-chain. $ID_{i,j}$ is the transaction index assigned by the blockchain, and $TS_{i,j}$ is the timestamp for the time lock of this particular transaction being received. The $I/O_{i,j}$ is the input and out messages for the transaction content where the script information in the $TX_{i,j}$ identifies the demand types and contents. A typical $I/O_{i,j}$ message is:

$$\begin{aligned} I/O_{i,j}:\{ & "prevOut":[...] \\ & "out":[\{type:"\lambda", \\ & "hash":"75cd51c2ds2g3hh439....", \\ & "script":\ "fe9efb29359ar332ec..."\ \}] \\ & \}, \end{aligned} \tag{2}$$

where *prevOut* contains the header information assigned from the sub-chain; *out* is the transaction body that contains the message type, λ, hash value of the transaction, and script details. The script is encoded in hexadecimal and the value of λ is listed as:

$$\lambda=\begin{cases} 0,\ credit\_check\_enquiry, \\ 1,\ means\_of\_production\_contract, \\ 2,\ manufacture\_log, \\ 3,\ audition\_inspection \end{cases} \tag{3}$$

(2) *Block structure:* Nodes will broadcast their transactions in the network, and network peers will check the signature and encrypt the transactions received in one timeframe into a block for verification. Except for the genesis block on the two sub-chains, the block structure is presented in Eq. (4).

$$\begin{aligned} & MBlock_i/CBlock_i=\{H_i,\ version,\ H_{previous}, \\ & \qquad RT_{merkle},\ TS_i,\ Nonce,\ Array\left[TX_i\right]\}, \\ & where \\ & \qquad H_{previous}=Hash\left(M/C\ Block_{i-1}\right), \\ & \qquad H_i=Hash\left\{ID_i,\ TS_i,\ En_i,\ Sig_i\right\}. \end{aligned} \tag{4}$$

The first (genesis) block does not contain the previous block hash $H_{previous}$. The block structure for CreditChain and M-InfoChain is the same, with the only difference being the transaction information *Array* [TX_i] in the block. H_i is the hash value of the block generated by the node, and RT_{merkle} is the root of the Merkle tree for transactions. And *version*, TS_i, and *Nonce*, represent, respectively, the version number for the blockchain, time stamps, and current nonce. The hash functions for calculating the previous and current block are defined above, where the key components include block index ID_i, timestamp TS_i, encrypted block contents En_i, and digital signature of the node, Sig_i.

4.3 Consensus coordination

4.3.1 CreditChain

In CreditChain, the customer checks the product credit randomly accessed by the User nodes in the P2P network. After receiving the query request from the customer, U_i aggregates and encapsulates it into a transaction which is then broadcast to other U_i nodes. Once the transaction is verified by transaction signature, structure and size, the transaction will be added to a new generated *CBlock* as check history log. Credit information is then retrieved from CreditChain.

Since CreditChain is a public blockchain with permission-less features for customers (except for the potential KYC registered recyclers), anyone is able to access the blockchain so that Sybile attack is most likely to occur by flooding check enquiries. Proof-of-Work (PoW)-based consensus mechanism is chosen to select the leader for block generation. The leader node $L(U_i)$ sacrifices computational power to gain the leadership and stands with Sybil attacks. PoW on CreditChain adopts the classic puzzle game to search for a nonce, *N*, that is smaller than the target value, where the target value is set to accommodate the average block generation time. The first customer node that finds the nonce, N, will be the leader in this round.

4.3.2 M-InfoChain

M-InfoChain is a consortium blockchain composed of two types of accounting nodes plastic producers, P_i and product manufacturers, M_i. Only P_i and M_i are authorised to aggregate transactions generated by the product contract codes and production logs and add new *MBlocks* to M-InfoChain. In order to reduce the computation cost for PlasticChain, a PBFT-based consensus mechanism is designed for M-InfoChain, where the algorithm design is demonstrated in Algorithm1. The consensus is achieved to decide the validity of a block. Accounting nodes in the system share messages among each other to commit a block to the chain. Malicious or dishonest nodes may broadcast tampered/fake blocks. As a result, the block could be identified by the most members of the nodes in the entire network.

Algorithm 1 Consensus Mechanism on M-InfoChain

```
msg(block); roundTime ← null
function Request(TXs(C/P_logs))
    State = NEW_ROUND
    proposer = get_proposer_address(M-InfoChain)
    if(current_miner == proposer)
        block = create_block(C/P_pool)
        broadcast_block(block)
        State = PRE_PREPARED
end function
```

function *Pre_Prepared(msg(block))*

ON msg(block).type == PRE_PREPARED

verify_block, validator(msg(block))

broadcast_prepare(msg(block))

State = PREPARED

end function

function *Prepared(msg(block))*

ON msg(block).type == PREPARE

verify_prepare, validator(msg(block).prepare)

prepare_POOL.add(msg(block).prepare)

if(prepare POOL.length >2f+1)

broadcast_commit(msg(block).prepare)

State = COMMITTED

end function

function *Committed(msg(block))*

ON msg(block).type == COMMIT

verify_commit, validator(msg(block).commit)

commit_POOL.add(msg(block).commit)

```
        if(commit_POOL.length >2f+1)
            commit_list = commit_POOL.get_commits()
            MBlock = block.append(commit_list)
            M-InfoChain.append(MBlock)
        State = FINAL_COMMITTED
    end function

    NEW_ROUND()
```

Each accounting node on M-InfoChain has five states at different sessions and messages during the new block *msg(block)* generation. In a new round, a proposer is selected in a round-robin fashion who sends a new block proposal which may contain the plastic contract codes or product production logs (*C/P_logs*). Then other accounting nodes become the validators awaiting entry to the PRE_PREPARED state. Validators will verify the proposed message with a new block and broadcast the *prepare* message to other validators. Both producer nodes P_i and manufacturer nodes M_i need to check the validity and authenticity of the means of production information, which forms a self-regulated body in the industry. They need to wait for $2f+1$ *prepare* messages, and then enter the PREPARED state, where a validator waits for $2f+1$ commit messages and then enters the COMMITTED state. Validators append the $2f+1$ commit messages into the block and add this new *MBlock* to M-InfoChain; they move into the FINAL_COMMITTED state after successfully adding a new block to M-InfoChain, where a new round will be initiated with a new proposer election.

Since PBFT can only tolerate the number of faulty nodes as less than one-third of all the nodes, it requires *3f+1* nodes in the system, where *f* is the maximum number of faulty nodes in the consortium. Therefore, *2f+1* approval from validator nodes is required when making decisions, and the more honest nodes on M-InfoChain, the more secure the consortium will be. The communication process is illustrated in Fig. 3. Moreover, when the credit information for plastic products changes on M-InfoChain, it automatically calls the smart contract to update the product information on CreditChain so that customers, U_i, are able to retrieve the latest credit information; and it links two sub-blockchains in an event-trigger manner.

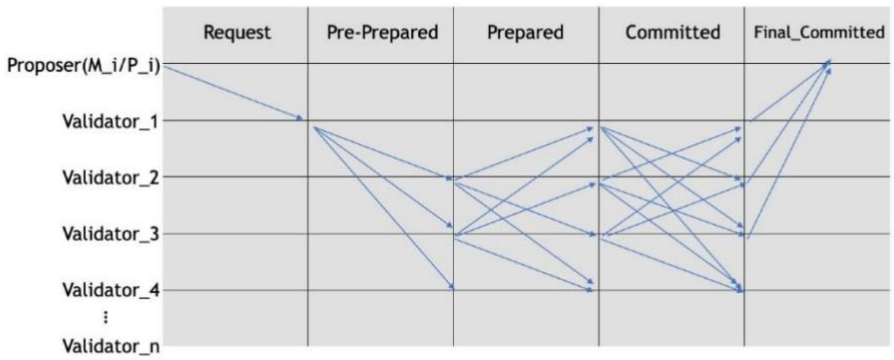

Fig. 3. The communication process on M-InfoChain.

5. Performance evaluation

In this section we examine the economic performance of the PlasticChain from the perspective of market mechanisms and consumer behavior, and thereafter analyze the computational and communication performance in order to evaluate overall system performance.

5.1 Economic impact

Plastic products, especially plastic packaging, have various substitutes in terms of plastic-type, composition and compound type. The plastic-type plays an important role, not only as a communication instrument between businesses and customers, but also in attracting the attention of consumers (Orzan et al., 2018). In order to analyze the full economic impacts of the PlasticChain credit, it is necessary to conduct a comprehensive analysis. We intend to carry out a thorough economic impact analysis in forthcoming research; however, at this stage we can deduce some possible economic impacts from the economic literature.

The plastic credit system is built on the assumption that, with appropriate information, customers will decide to purchase more recyclable and sustainable plastic products. So let us first examine how information can actually change consumer behavior.

In support of this assumption are several studies, where choice experiments for the number of product attributes presented to customers conducted by (Gao et al., 2009) suggest people's willingness to pay for some independent attributes in the food sector. Furthermore, authors in (Ward et al., 2011) suggest that information on certain energy usage for household appliances can increase their customers' willingness to pay. But a study conducted by the United States Department of Agriculture (Tegene A et al., 2003) is particularly interesting to our case. The study presents empirical evidence on consumer willingness to pay for biotech food based on the presence or absence of information labels. The research shows that particularly scientific information, i.e. demonstrable information, can increase consumer willingness to pay and thus shift the demand curve. It is therefore reasonable to expect that, in the implementation of plastic credit, customers will be increasingly inclined to purchase products due to the transparent and verifiable information given through the blockchain system.

The PlasticChain system promotes plastic products with higher recyclability by adding up a credit profile for the product and its corresponding company. Our second assumption is that consumers are willing to pay a premium for plastic products with higher levels of recyclability and thus which are more sustainable for the environment. Also, in this case the literature is ample, and includes organic food (EJ Van Loo et al., 2011), sustainable apparel (Hustvedt et al., 2008), among others. Recent studies (Katt F, et al., 2020; Merlino V.M. et al., 2020) have demonstrated the strong tendency for customers to purchase at a premium the products associated with environmental sustainability, recyclability and green features. Therefore, here too we can deduce that by introducing the PlasticChain we will observe a demand shift towards more recyclable plastic products.

The literature shows that the introduction of the PlasticChain may move consumers towards plastic products if information on recyclability is demonstrable; they are also willing to pay a premium for higher recyclable products. Our next step is to study the equilibrium conditions between consumer demand and plastic recyclable products. At present, the production of products made with recyclable plastic is more expensive than plastic made with raw materials (Gu F et al., 2017). We therefore need to model which level of recyclability will be acceptable for both consumers and producers in order obtain market clearing.

5.2 Computational and communication performance

Within this three-part section we implement the prototype of our proposed PlasticChain to evaluate the cost for computation and communication. We start by measuring the time consumption of processing the four types of transactions. Meanwhile, the computational time of different operations (algorithms) used as the components in the transaction is described. In the second part, the key parameters for designing *MBlock* and *CBlock* are used to estimate the capacity of these two types of block. Thirdly, we present the computational cost and communication overhead for the four types of transactions in our PlasticChain.

In the evaluation, we use two conventional computers (with Intel i5-4200H processor running at 3.30GHz) as a producer and a customer, and one small workstation (with Intel i7-8700 processor running at 4.20GHz) as a manufacturer to build up the simulation platform. The prototypes of M-InfoChain and CreditChain in our proposed PlasticChain are implemented with Python, a blockchain simulator called BLOCKBENCH (Dinh et al., 2017). To estimate the computational time cost and communication overhead of our prototypes of M-InfoChain and CreditChain, Hyperledger Fabric (version 2.2, PBFT-based consensus mechanism for consortium blockchains) is chosen to simulate the M-InfoChain, and Ethereum (PoW-based consensus mechanism for public blockchains) is selected to simulate the CreditChain in BLOCKBENCH. In addition, 256-bit ECDSA for signature, 128-bit AES for symmetric encryption, and SHA256 are used to measure the processing time of transactions with the cryptographic library, OpenSSL. Note that the selected key length (or hash length) can ensure that our prototype meets 128-bit security (Barker et al., 2012) in our experiments.

5.2.1 Processing time of transactions

To measure the processing time of different types of transactions, we measure the time consumption of the used major cryptographic operations on both the conventional computer (PC) and the workstation, with results shown in Table 1. Next, we thoroughly evaluate the time cost for generating four types of transactions designed in PlasticChain, including the transaction of contract codes, (TX_{cc}), the transaction of production log, (TX_{pl}), the transaction of credit updates, (TX_{cu}), and the transaction of log check, (TX_{lc}). According to the observed transactions in the simulator and the measured time cost of used cryptographic operations shown in Table 1, the average time to compute TX_{cc}, TX_{pl}, TX_{cu} and TX_{lc} is 9.773 ms, 13.475 ms, 6.618 ms, and 7.862 ms, respectively. Note that all the time results are the average of the results from 10,000 repeated experiments.

Table 1. The time cost of the major used cryptographic operations.

Operation	PC (ms)	Workstation (ms)
AES-128 (1MB, encrypt)	12.8	11.5
AES-128 (1MB, decrypt)	12.1	11.0
SHA-256	0.00501	0.00439
ECDSA (sign)	0.478	0.425
ECDSA (verify)	0.872	0.834

5.2.2 Capacity of the block

Based on our proposed block structures for M-InfoChain and CreditChain in Section III.b, it is necessary to regulate the length of the block header and body to determine the capacity of the block. In the block header, the lengths of Prehash, Index, and Merkle root are all set as 256 bits. Meanwhile, the lengths of Time (GMT) and Nonce are defined as 32 bits. On the other hand, in the block body, the lengths of Hash, ID and Signature are set as 256 bits, since it uses SHA256 and 256-bit ECDSA in our experiments. Therefore, the length setting of the key parameters in the block is summarized in Table 2.

The lengths of TX_{cc}, TX_{pl}, TX_{cu} and TX_{lc} are 1004, 274, 236, and 236 Bytes, respectively. After considering the size of the Merkle tree structure and other essential information, we find that 1MB *MBlock* can contain 981 TX_{cc} or 3102 TX_{pl}, whilst 1MB *CBlock* can contain 3495 TX_{cu} or TX_{lc}. When we assume one *MBlock* and one *CBlock* are generated per minute, the throughput of M-InfoChain can reach 16 TX_{cc} or 51 TX_{pl} per second, and the throughput of CreditChain can reach 58 TX_{cu} or TX_{lc} per second.

Table 2. The length (bits) of the parameters in each block.

Header	Prehash	Index	Nonce	Merkle root	Time
	256	256	32	256	32
Body	ID	Signature	Timestamp	Hash	
	256	256	32	256	

5.2.3 Computational cost and communication overhead

The next step is to demonstrate the computational cost and the communication overhead for M-InfoChain and CreditChain in our PlasticChain. Since customers can check the log or update the credit more frequently when compared with the contracts and production log uploading from the producers, we assume that a TX_{cc} and a TX_{pl} are generated every 120 minutes in M-InfoChain, and a TX_{cu} and a TX_{lc} are generated every 10 minutes in CreditChain by setting the mining difficulty and broadcasting latency in the simulator. Our experimental results are shown in Figs. 4 and 5. Note that the communication overhead is measured by capturing the network packets in the communications between the manufacturer computer and the producer computer, and between the manufacturer computer and the customer computer.

It is clear that both the computational cost and the communication overhead present the linear trend of increase as the usage time of PlasticChain grows. As depicted in Fig. 4, the time costs for computing transactions on M-InfoChain and CreditChain are 100.4 seconds and 750.6 seconds, respectively when the running time of PlasticChain reaches twelve months. Meanwhile, the communication overheads shown in Fig. 5 for transmitting transactions on M-

InfoChain and CreditChain are 5.80MB and 29.67MB, respectively when the running time of PlasticChain reaches twelve months.

For the designed consortium blockchain M-InfoChain, Hyperledger Fabric (PBFT-based) is selected in the simulation because its consistency is better than the public blockchains e.g., Ethereum (PoW-based) and Parity (PoA-based) (Dinh et al., 2017). Therefore, the PBFT consensus mechanism is more secure against security attacks forking the blockchain. However, the scalability of consortium blockchain using PBFT is limited because a consortium blockchain requires more consensus nodes to validate a transaction when compared with other public blockchains (Dinh et al., 2018). The number of producers is far fewer than the number of customers in our plastic management scenario, and hence a consortium blockchain is only used for the M-InfoChain.

For the designed public blockchain CreditChain, Ethereum (PoW-based) is applied in the simulation due to its higher scalability, which is more resilient to node failures; but one bottleneck of public blockchains is their vulnerability to forking attacks when the blockchain network scale is small (Li et al., 2020). In the proposed solution, the reason for choosing public blockchain as the CreditChain is that the scale of the customers is much larger than that of the producers so that enough nodes can be involved in the consensus process to avoid the forking issue.

Conversely, large communication overhead and low consensus efficiency are another two common bottlenecks of public blockchains (Xiao et al., 2020). Given that the scale of the CreditChain (public blockchain) is large, and numerous nodes are involved in processing transactions, high capacity and throughput network and high-performance nodes should be considered to sustain large communication overhead and support the highly efficient execution of consensus protocols in constructing the network infrastructure for the deployment of this blockchain-enabled solution to waste management.

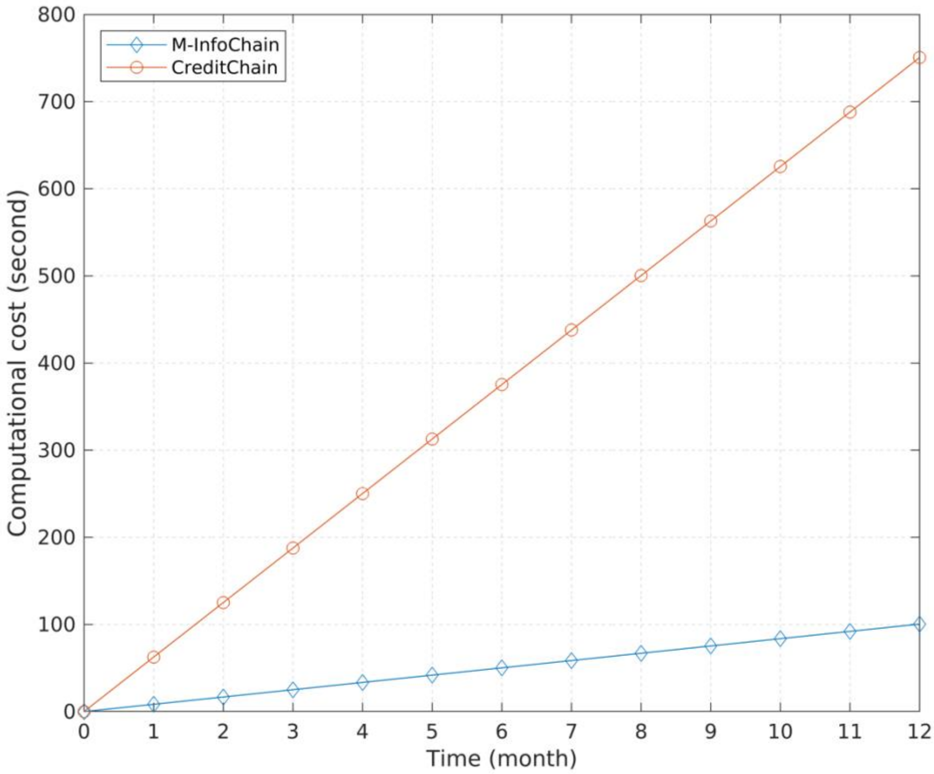

Fig. 4. The computational cost for generating transactions on M-InfoChain and CreditChain.

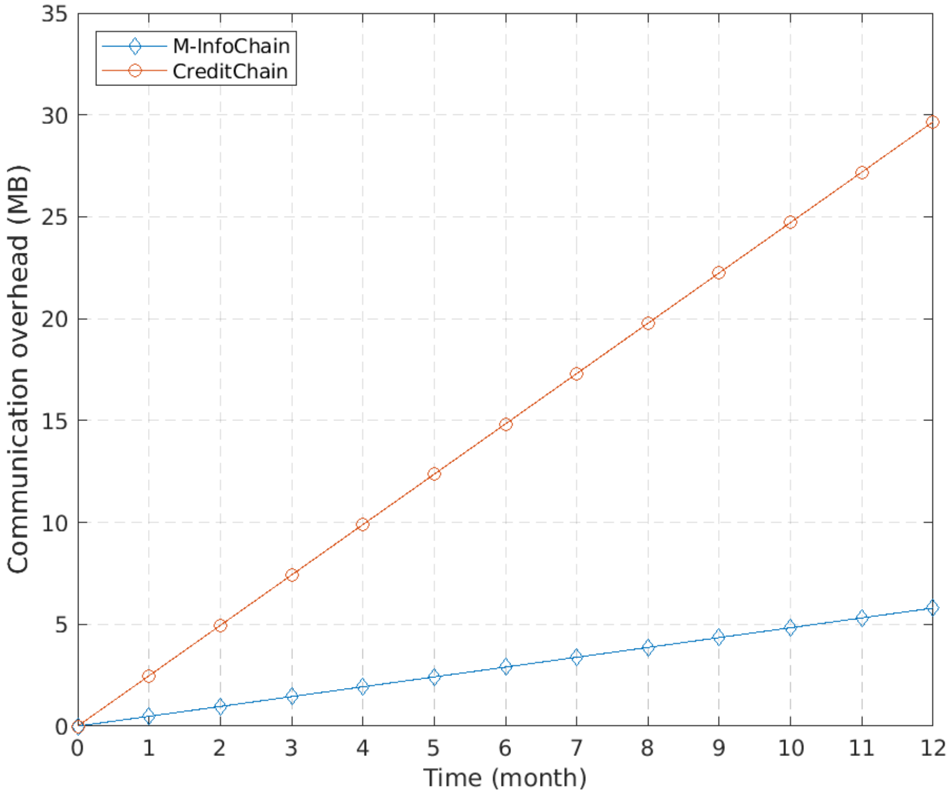

Fig. 5. The communication overhead for generating transactions on M-InfoChain and CreditChain.

6. Conclusions and future works

This paper has proposed a blockchain-based PlasticChain to generate and audit plastic products among manufacturers, producers, and customers. PlasticChain introduces the plastic credit into the market and integrates both plastic producers and customers. The system is effective in response to shifting customer demand towards more recyclable plastics, as it provides a unified and unambiguous system of reference.

The PlasticChain credit system uses a consortium blockchain M-InfoChain to ensure that the means of production for plastic products are audited by consortium members, thus allowing a self-regulatory body to be established between manufacturers and producers. Furthermore, the public blockchain CreditChain not only provides a platform but also a unified credit system for customers to securely check credit information on plastic recyclability. The system has been evaluated by means of an economic analysis (cost and demand), and by studying blockchain system performance (computational cost and transaction overhead). Results are summarized as follows:

- The economic analysis has demonstrated that demand could be shifted to mitigate the plastic product cost increase.
- The performance analysis of the computational and communication costs indicates that PlasticChain does not require a large amount of time or throughput to deal with transactions, so that it is indeed lightweight in reducing the resource requirement for the system maintenance.

However, in order to evaluate the projected amount of plastic waste to be reduced, the model does not provide sufficient variables for evaluation. Further information on the blockchain, e.g., customer check logs and access location, can be analyzed as indicators of pricing strategies for plastic product companies. A more precise pricing strategy for promoting increased numbers of recyclable plastic products would be beneficial towards the development of a positive feedback loop to reduce plastic waste. In addition, the impact of more advanced technique-assisted waste management systems discussed by Mousavi et al. (2020) and Mehrpooya et al. (2020), known as the exergoenvironmental method, will be considered in future work on environmental impacts.

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. This work was funded by the EPSRC and UKRI, under grant EP/S024883/1, and carried out at the UCL Plastic Waste Innovation Hub with the input of a multi-disciplinary team.

References

Allison, A.L., Ambrose-Dempster, E., T Aparsi, D., Bawn, M., Casas Arredondo, M., Chau, C., Chandler, K., Dobrijevic, D., Hailes, H., Lettieri, P., Liu, C., 2020. The environmental dangers of employing single-use face masks as part of a COVID-19 exit strategy.

Antelava, A., Damilos, S., Hafeez, S., Manos, G., Alsalem, S.M., Sharma, B.K., Kohli, K., Constantinou, A., 2019. Plastic Solid Waste (PSW) in the Context of Life Cycle Assessment (LCA) and Sustainable Management. Environ. Manage. 64(2), 230-244.

Aschehoug, S.H., Boks, C., 2013. Towards a framework for sustainability information in product development. International Journal of Sustainable Engineering. 6(2), 94-108.

Ayeleru, O.O., Dlova, S., Akinribide, O.J., Ntuli, F., Kupolati, W.K., Marina, P.F., Blencowe, A., Olubambi, P.A., 2020. Challenges of plastic waste generation and management in sub-Saharan Africa: A review. Waste Manage. 110, 24-42.

Bahij, S., Omary, S., Feugeas, F., Faqiri, A., 2020. Fresh and hardened properties of concrete containing different forms of plastic waste-a review. Waste Manage. 113, 157-175.

Bailey, I., Haug, B., O'Doherty, R., 2004. Tradable permits without legislative targets: a review of the potential for a permit scheme for sterilized clinical waste in the UK. Waste management & research. 22(3), 202-211.

Barker, E.B., Barker, W.C., Burr, W.E., Polk, W.T., Smid, M.E., 2012. Recommendation for key management part 1: General (revision 3). NIST special publication 800(57), 1-147.

Bernardo, C.A., Simões, C.L., Pinto, L.M.C., 2016. Environmental and economic life cycle analysis of plastic waste management options. A review. AIP Conf. Proc. 1779(1), 140001.

Deviatkin, I., Khan, M., Ernst, E., Horttanainen, M., 2019. Wooden and Plastic Pallets: A Review of Life Cycle Assessment (LCA) Studies. Sustainability 11(20), 5750.

Dinh, T.T.A., Wang, J., Chen, G., Liu, R., Ooi, B.C., Tan, K.L., 2017. BLOCKBENCH: A Framework for Analyzing Private Blockchains. In Proceedings of the 2017 ACM International Conference on Management of Data (SIGMOD '17). Association for Computing Machinery, New York, NY, USA. 1085–1100. https://doi.org/10.1145/3035918.3064033.

Dodbiba, G., Takahashi, K., Sadaki, J., Fujita, T., 2008. The recycling of plastic wastes from discarded TV sets: comparing energy recovery with mechanical recycling in the context of life cycle assessment. J. Cleaner Prod. 16(4), 458-470.

Dongyu, C., Weijun, L., Zhongli, P., Yun, X., 2012. Analysis on the necessity of introducing 3rd party personal credit to on-line lending. J. Henan College Financ. Manage. Cadres (1), 41-44.

Faraca, G., Astrup, T., 2019. Plastic waste from recycling centres: Characterisation and evaluation of plastic recyclability. Waste Management, 95, 388-398.

Farrell, M., Jones, D.L., 2010. Food waste composting: Its use as a peat replacement. Waste Management. 30(8-9), 1495-1501.

Fletcher, B.L., Mackay, M.E., 1996. A model of plastics recycling: Does recycling reduce the amount of waste? Resour. Conserv. Recycl. 17(2), 141-151.

Gao, Z., Schroeder, T.C., 2009. Effects of label information on consumer willingness-to-pay for food attributes. American Journal of Agricultural Economics. 91(3), 795-809.

Geyer, R., Jambeck, J., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci.

Adv. 3(7), e1700782.

Gu, F., Guo, J., Zhang, W., Summers, P.A., Hall, P., 2017. From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Science of the total environment. 601, 1192-1207.

Hogg, D., Elliott, T., Croasdell, S., Ballinger, A., Vergunst, T., Cullen, C., Bendali, L., 2011. Options and feasibility of a European refund system for metal beverage cans. Final Report, Appendix. 3.

Hogg, D., Sherrington, C., Vergunst, T., 2011. A comparative study on economic instruments promoting waste prevention. Final Report to Bruxelles Environment.

Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: Challenges and opportunities. Philos. Trans. R. Soc., B 364(1526), 2115-2126.

Horodytska, O., Cabanes, A., Fullana, A., 2019. Plastic waste management: Current status and weaknesses, in: The Handbook of Environmental Chemistry. Springer, Berlin, Heidelberg.

Hustvedt, G., Bernard, J.C., 2008. Consumer willingness to pay for sustainable apparel: The influence of labelling for fibre origin and production methods. International Journal of Consumer Studies. 32(5), 491-498.

Jaag, C., Bach, C., 2017. Blockchain technology and cryptocurrencies: Opportunities for postal financial services. In The changing postal and delivery sector . Springer, Cham. 205-221.

Jiang, T., Fang, H., Wang, H., 2018. Blockchain-based internet of vehicles: Distributed network architecture and performance analysis. IEEE Internet of Things Journal. 6(3), 4640-4649.

Katt, F., Meixner, O., 2020. A systematic review of drivers influencing consumer willingness to pay for organic food. Trends in Food Science & Technology.

Laroche, M., Bergeron, J., Barbaroforleo, G., 2001. Targeting consumers who are willing to pay more for environmentally friendly products. J. Consum. Mark. 18(6), 503-520.

Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T.H., Hauschild, M.Z., 2014. Review of LCA Studies of Solid Waste Management Systems--Part II: Methodological Guidance for a Better Practice. Waste Manage. 34(3), 589-606.

Liu, C., Chai, K.K., Lau, E.T., Chen, Y., 2018, April. Blockchain based energy trading model for electric vehicle charging schemes. In International Conference on Smart Grid Inspired Future Technologies. Springer, Cham. 64-72.

Marc, P., 2016. Blockchain technology: Principles and applications (No. halshs-01231205).

Gramoli, V., 2020. From blockchain consensus back to byzantine consensus. Future Generation Computer Systems. 107, 760-769.

Mehrpooya, M., Ghorbani, B., Mousavi, S.A., Zaitsev, A., 2020. Proposal and assessment of a new integrated liquefied natural gas generation process with auto–Cascade refrigeration (exergy and economic analyses). Sustainable Energy Technologies and Assessments. 40, 100728.

Merlino, V.M., Brun, F., Versino, A., Blanc, S., 2020. Milk packaging innovation: Consumer perception and willingness to pay. AIMS Agric Food. 5, 307-326.

Mousavi, S.A., Mehrpooya, M., 2020. A comprehensive exergy-based evaluation on cascade absorption-compression refrigeration system for low temperature applications-exergy, exergoeconomic, and exergoenvironmental assessments. Journal of Cleaner Production. 246, 119005.

Ølnes, S., Ubacht, J., Janssen, M., 2017. Blockchain in government: Benefits and implications of distributed ledger technology for information sharing. Government Information Quarterly

34(3), 355-364.

Onik, M.M.H., Ahmed, M., 2018. Blockchain in the Era of Industry 4.0. Data Analytics: Concepts, Techniques, and Applications, 259-298.

Orzan, G., Cruceru, A.F., Bălăceanu, C.T., Chivu, R.-G., 2018. "Consumers' behavior concerning sustainable packaging: An exploratory study on romanian consumers. Sustainability 10(6), 1787.

Peake, L., 2020. Plastic waste in the United Kingdom. In Plastic Waste and Recycling Academic Press, 585-600.

Rackovan, M.J., Akeley, J.P., Blackwell, C.J., 2018. Labels compatible with recycling. Nov. 20 2018, uS Patent 10,131,130.

Rajendran, S., Hodzic, A., Scelsi, L., Hayes, S.A., Soutis, C., Almaadeed, M.A.A., Kahraman, R., 2013. Plastics recycling: insights into life cycle impact assessment methods. Plast., Rubber Compos. 42(1), 1-10.

Rochman, C.M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H.K., Riosmendoza, L.M., Takada, H., Teh, S.J., Thompson, R.C., 2013. Classify plastic waste as hazardous. Nature 494(7436), 169-170.

Rolnick, A.J., Weber, W.E., 1986. Gresham's Law or Gresham's Fallacy? J. Political Econ. 94(1), 185-199.

Siddique, R., Khatib, J.M., Kaur, I., 2008. Use of recycled plastic in concrete: A review. Waste Manage. 28(10), 1835-1852.

Suter, M., 2019. Beyond PET: An Extended Deposit-Return System for Plastic Packaging in Sweden: A Qualitative Investigation of Challenges and Lessons from future and earlier Deposit-

Return Systems.

Tegene, A., Huffman, W.E., Rousu, M.C., Shogren, J.F., 2003. The effects of information on consumer demand for biotech foods: Evidence from experimental auctions (No. 1488-2016-123874).

Tomlinson, B., 2019. Recyclable liner for label assembly. May 9 2019, uS Patent App. 16/098,631.

Treleaven, P., Brown, R.G., Yang, D., 2017. Blockchain Technology in Finance. IEEE Comput. 50(9), 14-17.

Van Beukering, P.J., Bartelings, H., Linderhof, V.G., Oosterhuis, F.H., 2009. Effectiveness of unit-based pricing of waste in the Netherlands: Applying a general equilibrium model. Waste Management. 29(11), 2892-2901.

Van Loo, E.J., Caputo, V., Nayga Jr, R.M., Meullenet, J.F., Ricke, S.C., 2011. Consumers' willingness to pay for organic chicken breast: Evidence from choice experiment. Food quality and preference. 22(7), 603-613.

Van Rensburg, M.L., Nkomo, S.L., Dube, T., 2020. The 'plastic waste era'; social perceptions towards single-use plastic consumption and impacts on the marine environment in Durban, South Africa. Appl. Geogr. 114, 102132.

Verghese, K., Grant, T., 2005. LCA of degradable plastic bags. Centre for design at RMIT University,

Ward, D.O., Clark, C.D., Jensen, K.L., Yen, S.T., Russell, C.S., 2011. Factors influencing willingness-to-pay for the ENERGY STAR® label. Energy Policy. 39(3), 1450-1458.

Walker, T., Gramlich, D., Dumont-Bergeron, A., 2020. The Case for a Plastic Tax: A Review of

Its Benefits and Disadvantages Within a Circular Economy. In Sustainability. Emerald Publishing Limited.

Whitman, N.L., Begin, R.R., 2017. System for tracking waste or recyclable material including image documentation. Jan. 12 2017, US Patent App. 15/204,100.

Wikipedia, "Innocent Drinks," Accessed: Oct. 01, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Innocent_Drinks.

Xu, J., Xue, K., Li, S., Tian, H., Hong, J., Hong, P., Yu, N., 2019. Healthchain: A blockchain-based privacy preserving scheme for large-scale health data. IEEE Internet of Things Journal. 6(5), 8770-8781.

Zheng, Y., Yanful, E.K., Bassi, A.S., 2005. A review of plastic waste biodegradation. Crit. Rev. Biotechnol. 25(4), 243-250.