A Smart-Contract-Aided Plastic Credit Scheme

Xiaoshuai Zhang, Chao Liu, and Francesca Medda

***Abstract*—Researchers estimate that more than 8.3 billion tonnes of plastic have been produced since the early 1950s; however, only 9% of all plastic waste ever produced has been recycled. In this article, we propose a plastic credit driven system consisting of a recyclability index (RI) and plastic credit to impel plastic recycling and increase the quality of recyclable plastics through a market self-regulation mechanism. The RI is designed to evaluate the recyclability value of different plastic products based on their material compositions. The plastic credit, defined by the quantitative relation between the RI and product information, can be issued or traded by system stakeholders. Instead of setting rigid industry standards to regulate plastic quality, we construct a governance community among industry participants using blockchain-enabled smart contracts to self-regulate and monitor plastic production and trading. The proposed system is constructed on a consortium blockchain and a public blockchain to negotiate the RI, issue credits, and trade credits using smart contracts. Through the overall system performance analysis, the experimental results demonstrate that the designed plastic credit system can promote a demand shift toward plastic products with higher plastic recyclability and achieve a lightweight operation for resource requirements and system maintenance.**

***Index Terms*—Blockchain, plastic waste, recycling management, smart contract.**

I. Introduction

THERE are more than 350 million tonnes of plastic being used every year; however, less than half of it is properly collected and recycled [1]. COVID-19 has led to a pandemic of plastic pollution due to increased production of medical and protective equipment and takeaways [2]. Most plastic debris is harmful to the environment, where accumulating plastic wastes and toxic substances released from them could affect habitats and kill ecologically and commercially important species [3].

In response to the environmental issues, tradable permit schemes are becoming increasingly popular to encourage material recovery and the diversion of waste disposal and processing [4]. For example, the carbon market, which is premised on the theory that reducing emissions through trading, has been developed for over a decade with 25 existing carbon markets worldwide to offer emission trading schemes and offset schemes [5]. The offset scheme issues carbon credit for projects that reduce, sequester, or avoid emissions where funds could be invested in carbon-saving projects and organizations. Similarly, the U.K.'s Packaging Recovery Note (PRN) scheme, which was introduced in 1998, operates using market-based trading of waste permits between polluters relying on mandatory recycling targets to provide an incentive for trading [6]. The tradable permits allow companies to offset their pollution and are cost-effective compliance with environmental standards.

Inspired by the successful trading of carbon credit and PRNs, if a similar trading mechanism was applied in the plastic industry with market participation, it could promote a more circular economy environment to increase the industry's social responsibility to plastic uses. In the current carbon credit and PRN markets, credit issuing and circulation systems use centralized infrastructures where a trusted third party is needed to assess the quality and distribution of the credit [7]. For example, the Kyoto Protocol makes it mandatory for commercial entities emitting above the permitted limit of carbon dioxide to either cut down their emissions or buy carbon credit certificates, where the carbon credit is measured by each tonne of carbon dioxide or a corresponding amount of other greenhouse gasses. Then, the funds can be invested in ecological projects on the planet [5]. Similarly, in the plastic industry, Verra launched the Plastic Waste Reduction Standard to assess the plastic footprint, where plastic credits are issued and audited through the extent to which they can be recycled [8].

In the above centralized crediting systems, companies and organizations need to be responsible for the carbon/plastic they produce, use, or sell. Meanwhile, the credits are issued by an accredited third party, a reprocessor, as evidence of the receipt of a certain tonnage of plastic waste. However, such a centralized ecosystem generally has significant drawbacks, such as a crisis of trust caused by information asymmetry and information that can be tampered with easily as a form of corruption [9]. Moreover, the regulation and decision-making processes controlled by a single entity may restrict the development of plastic-related regulations and standards that are easy to fall behind the latest technological development or environmental issues, or even incur the monopolar effect to damage the whole ecosystem [10], [11]. Therefore, it is still challenging to meaningfully build up a large-scale plastic credit ecosystem that can attract more stakeholders to be involved and balance authorities of different roles in the ecosystem.

In this regard, blockchain or known as distributed ledger technology (DLT) can be a promising technical route to address this challenge by providing immutable records within a decentralized and fair environment. Blockchain has been widely applied

Manuscript received 4 January 2022; revised 6 June 2022 and 23 August 2022; accepted 3 September 2022. This work was supported in part by University College of London/Engineering and Physical Sciences Research Council Plastic Waste Innovation Hub. *(Corresponding author: Chao Liu.)*

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Digital Object Identifier 10.1109/JSYST.2022.3205266

in token economics to support credit generation and trading and provide the equitable management of credit information and the interface for the public to check on a secure distributed ledger [12]. Therefore, it can be a desirable structure for the collaboration among different entities such as individuals and corporations and technological solutions to manage credits that are shared among large groups of entities [13]. For example, global corporations, such as IBM and Dell, and governments propose numerous blockchain-based plastic recycling credit projects to encourage people to collect more plastic waste [14]. However, these projects cannot incentivize plastic producers and plastic product manufacturers to participate in or enable supervision by governments, plastics industry associations, and other nongovernmental organizations (NGOs) [15].

Instead of setting an industry standard from a single entity, this article proposes a self-governance community among plastic producers, plastic product manufacturers, governments, NGOs, and customers to be responsible for governing the plastic credit issuing, trading, and monitoring. A plastic credit scheme is implemented regarding to its recyclability defined by its recyclability index (RI), which is regulated through a governance executive voting mechanism by the industry participants on a DLT-enabled platform. Such a voluntary governance body is implemented on a blockchain platform using consortia smart contracts, which are responsible for facilitating on-chain voting in the form of governance votes conducted to maintain the plastic credit transparency and auditability. Furthermore, this plastic credit scheme considers market participation with the government and customers so that it could be open to public monitoring and receives the market response. This article addresses the above challenges to tackle the plastic recycling issues, and the novel contributions are summarized as follows.

1) Compared with our previous work [16], which only proposes an idea of plastic credit for the recycling market of plastic waste, the quantitative definitions of RI and plastic credit are proposed as a market catalyst in this article to define a plastic credit ecosystem with plastic producers, plastic product manufacturers, governments, NGOs, and customers participating in. The participants in this market can obtain credits from their recycled plastic waste and use credits to purchase more plastic material for their production.
2) To underpin our plastic credit scheme in a market environment, Ethereum blockchain is introduced to build the recycling market of plastic waste and transform the proposed plastic credit scheme into smart contracts. Compared with our previous work [16], which provides the architecture of the market consisting of a consortium and a public blockchains for plastic recycling management, this article focuses more on the operation of the plastic credit to propose three consortia smart contracts for voting RIs (or other proposals) and issuing and trading credits equally. A voluntary cooperative governance community can be established via the voting mechanism aided by the proposed consortia smart contracts to decide RIs, proposals, strategies, etc., and verify the traded and issued plastic credits in this DLT-enabled plastic credit scheme.
3) The proposed plastic credit scheme and smart contracts are implemented and simulated on the official Ethereum simulator Remix and the Ethereum test network, which are similar to practical marketplaces based on Ethereum, to verify the feasibility and evaluate the credit transaction performance in terms of computational cost, latency, and block size. Furthermore, to support more stakeholders joining the plastic credit ecosystem to facilitate plastic recycling and utilization in the future, the scalabilities of two prevalent Ethereum implementations that can deploy our smart contracts are analyzed in terms of consensus mechanisms, transaction per second (tps), and transaction fee.

The rest of this article is organized as follows. Section II presents the related work about blockchain use in the management of plastic recycling. Then, the definitions for RI and plastic credit are illustrated in Section III. The plastic credit scheme architecture and design principles are demonstrated in Section IV, which is followed by the concrete implementations of the proposed consortia contracts illustrated in Section V. After that, the system simulation for the smart contracts and the performance evaluation are conducted and analyzed in Section VI. Finally, Section VII concludes this article.

II. Related Work

Benefiting from the point-to-point network, transparent transactions, and immutable ledgers underpinned by blockchain, numerous sectors are advanced to evolve toward the decentralized era, such as finance, smart cities, and circular economy [12], [17], [18]. Since blockchain can drive equivalent collaborations in various entities for negotiation, trading, information sharing, etc. [13], plastic credit designed based on blockchain can leverage the following merits of blockchain technology:

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 the carbon credit area to offset carbon footprint, blockchain technology has been widely applied to track carbon emission and encourage to produce and use clean energy. SolarCoin [19], for example, uses a blockchain platform to incentivize solar energy producers by rewarding every megawatt hour of electricity they produce with one free SolarCoin. This digital reward can be used as a medium of exchange or converted to any other currency. Project Earth Dollar [20] aims to link carbon credits (pollution permits that are issued for emissions avoided elsewhere) to blockchain tokens (representations of a particular asset or utility within the platform). Ecosphere+, a natural asset management company based in Luxembourg, is supplying carbon credits to intermediaries using blockchain tokens, where carbon credits originate from conservation efforts in Peru's Cordillera Azul National Park [20]. These credits are being provided to the Maltese strategic partner of Ecosphere+, Poseidon, whose blockchain platform allows consumers and retailers to track and offset their carbon footprints to tackle climate changes [21].

To tackle plastic waste issues, some traditional projects have been proposed without using blockchain technology. Suter proposed a deposit-refund system (DRS) [22] to encourage the return of materials to increase the use of refillable. DRS can be applied in collecting beverage containers and tires, but this project did not consider the reuse of the collected materials. Milios et al. [23] analyzed the chain market of plastic recycling and pointed out a major challenge in plastic recycling, i.e., there is no standard type of plastic or plastic recycling design to manage the whole recycling process, in which plastic producers and plastic-consuming companies can participate. By introducing a clear quantitative measurement of plastic recyclability, our environment can benefit from verifying the recyclability of plastic products by customers in the market and encouraging the sale and production of recyclable plastic. To manage plastic recycling and utilization, one method is to require governments or plastic organizations to design-related regulations and standards for plastic companies to follow. Although this method is straightforward to be carried out, such a centralized decision method may not be fair enough for all the companies. Furthermore, it is not easy to rely on only governments or several NGOs to monitor all the plastic companies in plastic recycling and manufacturing. Therefore, we believe that a self-regulatory body using a consortium blockchain to define and monitor its own industry standards could be more equitable and efficient than a traditional uniform standard set by a third party [16], where blockchain with the decentralized characteristic is a promising solution to tackle the accelerated plastic waste issues.

Since blockchain is a new technology that has emerged and been applied in diverse sectors for only a few years, the research on blockchain use in plastic recycling is still in its infancy. Mondal and Kulkarni [24] suggested utilizing blockchain in plastic waste management but only proposed a simple framework without any concrete smart contracts or duties of different entities involved in plastic recycling. Meanwhile, there are several projects of plastic recycling applying blockchain. IBM released a blockchain-based token reward platform, Plastic Bank, which can incentivize people to recycle more plastic waste with valuable commodity compensation [25]. Similarly, Reward4Waste published the CryptoCycle token to encourage more users to collect more plastic waste [26]. Apart from incentivizing plastic waste recycling by blockchain-based monetization, Dell [27], Empower [28], RecycleGo [29], and Waste2Wear [30] are employing blockchain to track plastic waste in its recycling, transportation, and reusing.

However, these projects only consider encouraging people to recycle more plastic waste but lack the consideration of incentivizing plastic producers to adopt more recyclable plastic in their productions. Furthermore, current solutions cannot evaluate the recyclability of different plastic materials and productions quantitatively or support the participation of other supervisory roles such as governments and NGOs to evaluate recycling processes and outcomes. In addition, the projects' owners still act as the dominant roles in the mentioned projects without any negotiation mechanism that may prevent the decentralized management of plastic recycling and utilization [31]. Our previous work [16] is the first proposed architecture to apply blockchain technology to manage plastic waste recycling involving different roles in manufacturing plastic production. Plastic producers and the intermediary (manufacturers) can manage the recycled plastic in a consortium blockchain in the proposed architecture. Meanwhile, the intermediary can record the credits of different plastic products in another public blockchain for customers to check. However, the clear quantitative relations between plastic credits and different plastic types still need to be discussed and proposed to formalize incentivizing strategies in the plastic waste recycling marketplace to attract more stakeholders to participate in.

Although blockchain and DLT, as a new method and a new structure to be applied in various fields, are attractive to investors, the mass adoption of tokens to raise funds forced the tightening of regulations by governments due to issues like scams or failures of certain token ecosystems [32]. Hence, well-designed systems, robust regulations, and appropriate incentives are essential to achieving long-term outcomes of blockchain autonomous ecosystems. In current studies on blockchain-enabled plastic recycling, despite some high-level blockchain-based architectures proposed to manage plastic recycling, there are still no concrete guidelines or protocols to regulate the recyclability of different plastic products and the quantity relations between credit and different types of plastic in the recycling process.

III. Proposed RI and Plastic Credit

According to discussions with Plastic Waste Innovation Hub at the University College of London, we adopt the following fair assumptions for RI and plastic credit definitions.

1) The plastic credit scheme is implemented in average waste-processing-level countries where the plastic recycling infrastructures can support the mechanical recycling process [33].
2) The recycling process does not consider compostable plastic material, so the recyclable plastic material can still be circulating in the plastic credit scheme.

In this section, the quantitative relation between plastic material RI and its corresponding composite product RI is first established to define the product RI. Then, the quantitative relation between plastic material RI and plastic credit is demonstrated in Section III-B.

A. Plastic RI

There are two indices of plastic recycling to be discussed in this part, including plastic material RI and its corresponding composite plastic product RI. The plastic product RI is a value to represent the recyclability of the plastic product, which measures its physical characteristics of how much it can be recycled. Higher plastic product RI implies that the product contains more recyclable material and is more eco-friendly. Similarly, a plastic material RI can indicate the recyclability of one type of plastic material, which should be negotiated by consortium members, which usually are producers, manufacturers, plastics industry associations, governments, and other NGOs. After plastic material RIs are determined, the plastic product RI can be formulated as follows to establish the relation with the plastic material RI:

$$P_{\mathrm{RI}} = \frac{1}{n}\sum_{i=1}^{n} p_i \cdot P_{\mathrm{RI},i}$$

$$P_{\mathrm{RI},i} = \frac{1}{m}\sum_{j=1}^{m} \mathrm{RI}_j \cdot p'_j \cdot C_P$$

where P_{RI} is the recycling index of the product P, $P_{\mathrm{RI},i}$ represents the RI of the part i in the product P (e.g., a lid of a bottle), p_i is the proportion of i in P, RI_j is the recycling index of the material j that is negotiated by consortium members, and p'_j is the proportion of the material j in the part i. Note that if the type of plastic material is not recyclable, its corresponding RI should be 0 in calculating P_{RI}. C_P is an index representing the difficulty level of disassembling the composite plastic product using a mechanical recycling process ranging from 0 to 1, where 1 denotes the product can be fully disassembled. As this article assumes a fairly simple scenario, we use a binary index $C_P \in \{0, 1\}$ to run the simulation.

Notably, we apply the average term in calculating the plastic product RI because our design aims to avoid manufacturers producing plastic products with more parts, which is more harmful to the environment in most cases [34]. Such a term can encourage plastic product manufacturers to make products with a fewer number of parts and fewer types of material. For example, there are two different manufacturing processes *A* and *B* to produce one plastic product *P*. In the process *A*, *P* is made of two equal parts each having an assumed $P_{\mathrm{RI},i}$ of 0.6. Therefore, the plastic product RI of *A* can be calculated by $P^A_{\mathrm{RI}} = \frac{1}{2}(0.5 * 0.6 + 0.5 * 0.6) = 0.3$. In contrast, *P* is made of four equal parts each having an assumed $P_{\mathrm{RI},i}$ of 0.6 in the process *B*. In this condition, the plastic product RI of *B* is $P^B_{\mathrm{RI}} = \frac{1}{4}(0.25 * 0.6 + 0.25 * 0.6 + 0.25 * 0.6 + 0.25 * 0.6) = 0.15$. This analysis clearly shows that using fewer parts and material types to make the same product can achieve higher product RI, which is more eco-friendly.

B. Plastic Credit Definition

The plastic credit can quantitatively represent the amount of the recyclable material that a manufacturer could use for purchasing raw plastic materials. In our proposed plastic credit scheme, manufacturers can consume their plastic credits to purchase raw plastic material using their annual caps of plastic consumption. The relationship between RI and its corresponding plastic credit is negatively correlated, which means that a higher RI parameter is more recyclable so that manufacturers could consume fewer plastic credits to obtain these raw plastic products. The initial annual caps of plastic consumption for different plastic product manufacturers should be evaluated and negotiated by the consortium members, including plastic producers and manufacturers, plastics industry associations, governments, and NGOs in terms of their manufacturing capability, plastic consumption history, etc. Meanwhile, the annual plastic credit distribution among all the manufacturers can also be determined by the consortium members. The above negotiation

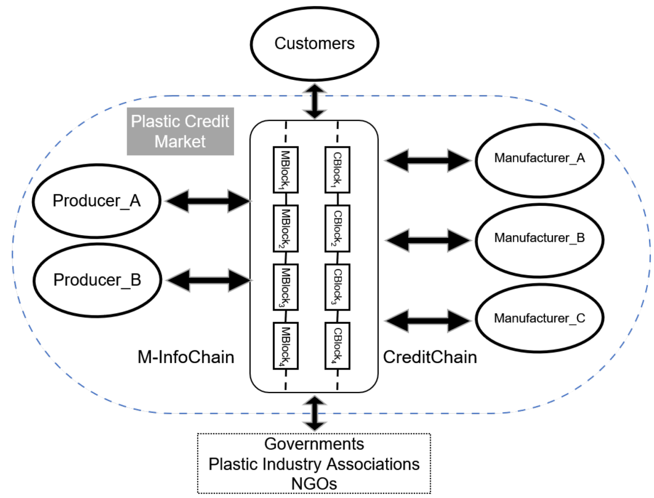

Fig. 1. System architecture of the plastic credit scheme.

and distribution can be supported by voting and issuing designed in our consortia smart contracts (see Section V). The plastic credit CR, which is generated by the producer side, can then be formulated as follows:

$$CR_i = \frac{m}{\sum_{j=1}^{m}(\mathrm{RI}_j \cdot p_j)}$$

$$CR = \sum_{i=1}^{n} CR_i \cdot w_i \cdot N_i$$

where RI_j is the RI of the recyclable material j, p_j is the proportion of the recyclable material j in the product i, w_i represents the weight (kilogram) of a product i, and N_i is the number of recycled product i. Note that m should only consider the number of recyclable plastic material types in the product i. Meanwhile, if the type of plastic material is not recyclable, its corresponding RI_j should be capped with a maximum number CR_{Max} in calculating CR, which should be defined by the real-world scheme implementation.

To encourage plastic companies to make plastic products using more recyclable material, their annual caps of plastic consumption can be increased in terms of their annual yield of recyclable plastic products, which can be calculated by $Y = \sum_{i=1}^{n}\sum_{j=1}^{m}(\mathrm{RI}_j \cdot p_j) \cdot w_i \cdot N_i$. Similarly, if a plastic producer produces more Y or a plastic product manufacturer consumes more Y, its annual plastic credit distribution in the next year can be increased and vice versa. In addition, to incentivize small- and medium-sized enterprises (SMEs) to join the blockchain-based plastic credit system, some strategies can be applied such as an extra annual cap of plastic consumption and a plastic credit discount for purchasing recyclable plastic. It should be mentioned that the related rules and standards should be discussed and established by plastic associations and NGOs with representatives from different SMEs.

IV. Plastic Credit Scheme Architecture

As illustrated in Fig. 1, the plastic credit scheme consists of two parallel blockchains with four groups of stakeholders, including plastic producers, plastic product manufacturers, customers, governments, plastics industry associations, and other NGOs. Negotiations about RIs, annual caps of plastic consumption, and annual plastic credit distribution can be achieved on M-InfoChain by voting in the consortium members involving plastic producers, plastic product manufacturers, governments, plastics industry associations, and other NGOs. Meanwhile, the proposed scheme supports credit issuing from government or NGO nodes and credit trading in the plastic credit market formed by manufacturers and producers on M-InfoChain. In addition, CreditChain is used to share plastic information with customers. This section is divided into two parts that, respectively, explain stakeholders' roles and functions and the blockchain structure.

A. Plastic Credit Scheme Stakeholders

1) *Producers:* A plastic producer node is a company that can produce raw plastic material (e.g., plastic bags, films, and bottles) with different plastic material types such as PET, PP, HDPE, or any potential recyclable material. All the raw plastic products from producers need to be registered and verified for its recyclability assessment by uploading the information of the plastic material to M-InfoChain. The information contains the plastic formula and composition documents so that the credits can be calculated by its corresponding RI and quantity. Then, the information and the amount of the credits to be issued need to be checked and verified by consortium members via consensus coordination to create valid transactions on M-InfoChain. Note that a plastic producer can also be a plastic manufacturer if it needs to buy or sell credits on the M-InfoChain.
2) *Manufacturers:* A plastic manufacturer node is a company that utilizes raw plastic material to manufacture various products, e.g., shampoo, juice, and milk. An example could be soft drink companies such as London-based Innocent Drinks, who sells drinks bottled in plastic containers. Each manufacturer has a credit quota (cap) in a period (e.g., a year), which is determined by the consortium members and then allocated by the government regulators or other NGOs, to purchase recycled plastic from producers. If a manufacturer uses up its annual credit quota, this manufacturer can either buy more credits on M-InfoChain to purchase more raw plastic material from plastic producers or other manufacturers who have excess plastic credits; otherwise, the manufacturer has to switch to the raw plastic material with higher RI.
3) *Customers* can obtain information about the RI of each different plastic material and plastic product. Such information sharing may encourage customers to purchase more plastic products with higher RI to promote the use of more recyclable plastic. It is important that customers can also share their consumption habits of different plastic products via the plastic credit scheme blockchain to assist governments and NGOs in conducting the market and demand analysis about different types of recyclable plastic material.
4) *Governments* and NGOs can be the plastic credit issuers in the plastic credit scheme. Also, governments or NGOs can supervise plastic recycling and trading by auditing the transactions on M-InfoChain and CreditChain. Based on data analyses of transactions, NGOs can check the quantity of the produced plastic from different plastic producers and the types of recyclable plastic demands of different plastic manufacturers. Furthermore, NGOs and investors can analyze the blockchain data to determine the producers and manufacturers who increase recycling or decrease plastic use. The analysis results can guide investors' investments to support prominent recycling companies and organizations.

In order to battle the increasing level of plastic waste, there are two options to choose from: imposing a tax [35] on plastic consumption companies and setting a plastic credit quota for manufacturers. Taxes and levies could be applied. However, for these to be successful, sustainable alternatives must be readily available at a competitive price; otherwise, it could be unpopular with many consumers, especially in the short term, as these taxes would be added to the final product price. The plastic credit scheme in this article uses the plastic credit quota to address the plastic waste challenge by utilizing the market power [16], where the ultimate advancements in material and recycling process are driven by the market choice.

B. Blockchain Structure

M-InfoChain is a consortium blockchain for negotiating the RI of different types of plastic material, issuing and trading credits, and purchasing recycled plastic, which is the core module of the plastic credit scheme. Registered plastic producers, plastic manufacturers, governments, and NGOs can be the participants of M-InfoChain to determine the RI via voting in the consortia smart contracts, which will be explained in detail in the next section.

When plastic producers generate raw plastic material, they can request the corresponding credits from M-InfoChain (like mining in Bitcoin) based on its corresponding plastic material RI. Meanwhile, plastic manufacturers can use their credits to purchase raw plastic material from plastic producers. In the case of credit transferring or trading, these activities are also executed on M-InfoChain. Such transactions can be recorded in M-InfoChain. In addition, negotiations (voting) of annual plastic credits and plastic consumption caps for different plastic product manufacturers can be supported by the corresponding smart contracts and saved in M-InfoChain. At each time frame, a node from the consortium is selected as the leader to aggregate valid transactions and generate new blocks ($MBlock_i$) on M-InfoChain. For example, credit issuing and recycled plastic purchase activities can result in credit updates to certain plastic producers and plastic manufacturers. Such activities can call the smart contract to create valid transactions on M-InfoChain. The structure examples of three types of transactions, voting, issuing, and trading, are shown in Fig. 2. Each transaction contains two parts: header and content. The header contains the sender's address, the receiver's address, and the transaction's hash. Meanwhile, the content involves the sender's signature of the transaction. Furthermore, the content of the voting

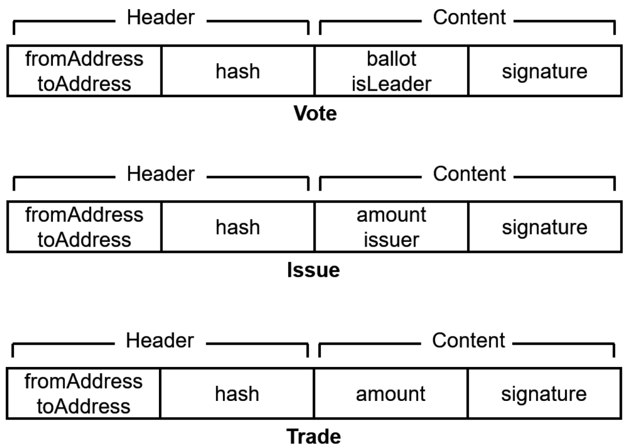

Fig. 2. Transaction structures of vote, issue, and trade in M-InfoChain.

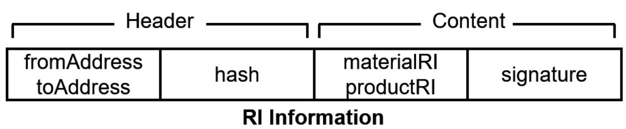

Fig. 3. Transaction structure of RI information in CreditChain.

transaction consists of a ballot (or the voting result from the leader) and a Boolean *isLeader* to show if the sender is the voting leader. The transacted amount of plastic credit is involved in the content of both the issuing transaction and the trading transaction. In addition, an additional parameter *issuer* shows the credit issuer in the content of issuing transaction.

CreditChain is a public blockchain to support plastic manufacturers to publish RIs of different plastic materials and the RIs of their products calculated from the RIs of the contained plastic material, which is open to the general public. Note that customers who are public users are not involved in the RI negotiation and voting process. In addition, governments and NGOs are also granted access to audit CreditChain and collect customers' consumption habits of different plastic products to measure the popularities of different plastic products to analyze the demands of different types of plastic material. The structure example of the RI information's transaction is shown in Fig. 3, which is similar to the above three transaction structures. Note that the content can involve not only the material RI or the product RI to be published, but also plastic knowledge, the amount of recycled plastic and manufactured plastic products, etc., for the public.

V. Consortia Smart Contracts

In this section, the core modules of consortia smart contracts for consortium members to negotiate RI and conduct operations on plastic credits are illustrated in Fig. 4, including plastic material RI negotiation and plastic credit operations for building up our proposed plastic credit scheme, whereas plastic credit operations include credit issuing and credit trading. The implemented smart contract of voting can be used to negotiate not only RI but also annual plastic credits, annual plastic consumption caps of different companies, incentivizing strategies for SMEs, and so on.

Algorithm 1: On-Chain RI Executive Voting.

Inputs: $VT = \{Voter_i, i = 1 \ldots n\}$, $MaterialInfo$, $ProposalRI = \{RI_j, j = 1 \ldots m\}$.
Outputs: $WinnerRI \in ProposalRI$
Initialize: $List_{\text{vt}} \leftarrow VT$, $List_{\text{ri}} \leftarrow ProposalRI$
  $List_{\text{count}} \leftarrow \{0, 0, \ldots\}$, $|List_{\text{count}}| = |List_{\text{ri}}|$.
procedure Retrieve$void$
  return MaterialInfo
end procedure
function VoteRI_{index}
  if $1 \leqslant RI_{\text{index}} \leqslant m$ **then**
    $List_{\text{count}}[RI_{\text{index}}] = List_{\text{count}}[RI_{\text{index}}] + 1$
  end if
end function
  for $(i = 1, i \leqslant n, i++)$ **do**
    request $List_{\text{vt}}[i]$ to execute Retrieve
    request $List_{\text{vt}}[i]$ to execute Vote
  end for
request $Voter_{\text{chair}} \in List_{\text{vt}}$ to execute
  $WinnerRI \leftarrow List_{\text{ri}}[MAX(List_{\text{count}}).index]$
  return $WinnerRI$

A. Plastic Material RI Negotiation

The plastic material RI negotiation occurs on-chain and can be accessed through the consortium M-InfoChain members, including plastic producers, plastic product manufacturers, governments, plastic industry associations, and other NGOs, forming the governance community through executive voting. This voting process can measure the sentiment of consortium members. Furthermore, it can be utilized to negotiate RI, its corresponding product RI, and the plastic credit according to the material information proposal submitted by producer nodes and approved by the consortium members. In the RI negotiation process, producers and manufacturers consist of the executive voters. When active, an executive producer node proposes a set of plastic material information that is going to be voted on the on-chain RI executive voting smart contract. All the voters (i.e., all consortium members) can retrieve the material information before voting. Meanwhile, each voter should select one option from all the RI proposals to determine the winner (i.e., the RI proposal that receives the most ballots) for the voted material. Whenever a proposal for a new type of plastic material is submitted, the consortia smart contract is called and executed, where an exemplar algorithm (pseudocode) is demonstrated in Algorithm 1.

In every vote, a voter from all the voters is assigned as the voting chair to announce the winner RI, where each voter is weighted equally within the voting contract. The equal weight mechanism could prevent data manipulation in the consortium blockchain [36], whereas governments, plastic industry associations, and other NGOs are also connected to the M-InfoChain for voting, auditing, and monitoring. Each voting requires a single transaction and typically does not cost a few cents, which will be analyzed in Section VI. The voting period of a given executive voting call varies, which can be set from three to seven day periods. Meanwhile, all the RI proposals ($List_{\text{ri}}$) and their

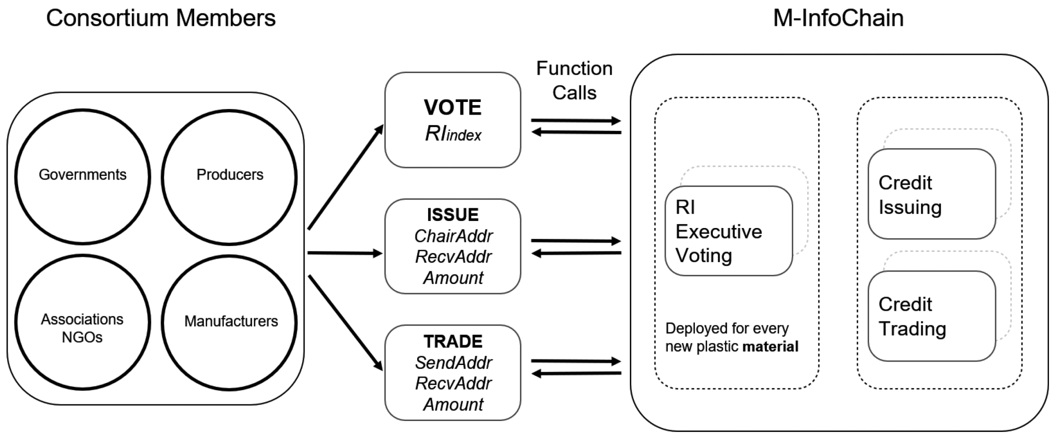

Fig. 4. Core modules of consortia smart contracts in the plastic credit scheme.

Algorithm 2: Plastic Credit On-Chain Operations.

Inputs: $ChairAddr, SendAddr, RecvAddr, Amount.$
Initialize: $SendBal \leftarrow SendAddr.balance,$
$RecvBal \leftarrow RecvAddr.balance,$
require $Amount > 0.$
function Issue$ChairAddr,\ RecvAddr,\ Amount$
 if $ChairAddr \neq RecvAddr$ **then**
  $RecvBal = RecvBal + Amount$
 end if
end function
functionTrade$SendAddr,\ RecvAddr,\ Amount$
 if $Amount \leqslant SendBal$ **then**
  $SendBal = SendBal - Amount$
  $RecvBal = RecvBal + Amount$
 end if
end function

corresponding ballot counting result ($List_{\text{count}}$) should be visible to all the voters to verify the vote results. In addition, government or regulation bodies are encouraged to audit the code for each vote to increase its transparency and accountability.

B. Plastic Credit Operations

The two functions *Issue* and *Trade* are shown in Algorithm 2. Note that the *Amount* required in the function *Issue* should be determined through the negotiation by the government regulators, related plastic industry associations, and other NGOs depending on different applied scenarios and stakeholders. Furthermore, before *Trade* function is invoked in the plastic credit market, certain consensus procedures (similar to vote) should be considered to allow every participant (producers and manufacturers) of the system to know and verify the amount used in the trading smart contract to reach an agreement to the amount between all the participants.

Instead of involving mining strategies and public miners, the proposed plastic credit scheme can utilize the equation CR to determine the credit amount generated from RI, and attract producers and manufacturers to form a consortium to verify the amount to be issued or traded to achieve consensus results. By eliminating the mining process, it saves computation power and communication cost for generating a new block and also reserves the transaction transparency. In this way, the system ensures local autonomy while reserving the right for governments, plastic industry associations, and other NGOs to roll ledgers back under emergency situations.

VI. System Analysis

In this section, we implement the prototype of three smart contracts in our proposed plastic credit system to evaluate the time and gas consumption for computation and communication. Furthermore, we measure the data size of each kind of transactions (i.e., vote, issue, and trade) to estimate the growth trend of transactions' data size. Specifically, this section can be divided into three parts. First, the time consumption of three kinds of transactions is measured, respectively. Then, the gas cost of *Vote*, *Issue*, and *Trade* operations is examined on the Ethereum test network. In the third part, we present the block data size of each kind of transaction to estimate the growth trend of the transaction size for our proposed plastic credit system in the future.

We choose a common language of smart contract Solidity to implement our proposed smart contracts in the evaluation. One small workstation (with Intel Core i9-10850K processor running at 4.8 GHz and 32-GB memory) and Ethereum Remix[1] are used as the client and as the network simulator to run the Ethereum test network (in Remix) to build up the experimental platform, respectively. The solidity compiler version we adopt is 0.8.7, and the Ethereum network engine of Remix is JavaScript Virtual Machine (JVM), which can simulate an Ethereum network in local memory. In addition, the number of Ethereum nodes deployed in JVM is 20, and the gas limit of each node for executing a smart contract is 3 million Gwei.[2] Note that in the initialization of the test network, every node is assigned an Ethereum address and is allocated 100 ether to cover the gas cost of executing different smart contracts.

[1]Remix is an official development environment of smart contract for Ethereum, can be found at https://remix.ethereum.org/.
[2]Gwei is a unit of gas in Ethereum, 1 Gwei $= 10^{-9}$ ether.

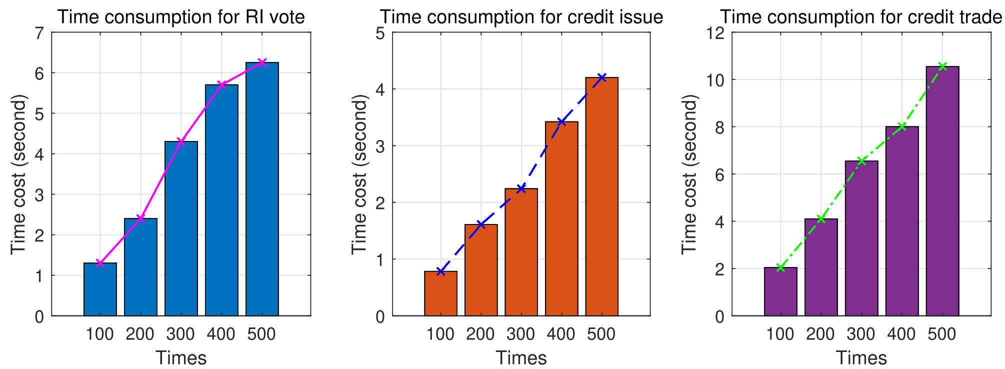

Fig. 5. Time consumption of three kinds of transaction: vote, issue, and trade.

TABLE I
TRANSACTION PER SECOND OF THREE TYPES OF TRANSACTION

Transaction type	Transaction per second (tps)
Vote	77
Issue	128
Trade	49

TABLE II
GAS CONSUMPTION OF THREE TYPES OF TRANSACTION

Transaction type	Gas consumption on Ethereum test network (wei)	
	1st	other
Vote	92923	73011
Issue	46823	29735
Trade	47798	35102

A. Transaction Time Consumption

In this part, the time consumption of three kinds of transaction, i.e., vote, issue, and trade, is evaluated. The number of material RI proposals to be voted on is set to 10 to deploy the RI vote smart contract. Meanwhile, the amount of plastic credit issued or traded in the corresponding smart contract for the experiment is set to an integer between 10 and 500 randomly for every run. All the three kinds of transactions are executed 100, 200, 300, 400, and 500 times to obtain the result of time cost, which is depicted in Fig. 5.

On average, a vote transaction consumes 13.0 ms, whereas an issue transaction only requires 7.8 ms, which is about half the time consumed by the vote transaction. Meanwhile, a trade transaction uses the most time, 20.5 ms. It is clearly shown in the three subfigures that the time cost of the three types of transactions increases by the running times linearly. This result implies that the time cost of issue and trade is not associated with the number of plastic credits involved in transactions. Furthermore, the corresponding tps of three kinds of transactions is shown in Table I.

Therefore, such time consumption in the millisecond scale to operate smart contracts using the proposed plastic credit system is acceptable for clients, including plastic producers and manufacturers. The tps result also indicates that the proposed smart contracts can be applied to plastic recycling management systems including large-scale users.

B. Transaction Gas Cost

After evaluating the transaction time consumption, we measure the transaction gas cost of the three kinds of transactions (i.e., vote, issue, and trade) with the same experimental settings as the experiments of transaction time consumption in Section VI-A. All the three types of transactions are executed ten times to observe the variation of the gas cost in transactions. The experiment results are demonstrated in Table II, where "1st" means the first time that an account (address) receives a ballot from vote or an amount of plastic credit from issue or trade. "Other" represents an address that receives ballots or plastic credit at other times. Note that the unit of gas cost is wei, whose relation to ether is 1 ether $= 10^{18}$ wei. The results manifest that the scale of the gas consumption is around 10^{-14} ether, which is negligible when compared with the amount of the plastic credit (10–500) involved in transactions.

It is clear that the gas cost of the first time is more than the other times in this experiment because when it is the first time an address receives a ballot or an amount of plastic credit, the Ethereum Virtual Machine requires an extra gas cost to allocate new space for the ballot or credit variables in the memory. After the first time, the gas consumption of each transaction type can keep stable, i.e., the gas consumption does not vary by different numbers of plastic credit in transactions. This result indicates that such gas consumption is affordable to every participant in the proposed plastic credit system.

C. Transaction Size

In this section, the transaction size of the three types of transactions is measured with the same experimental settings as the experiments of transaction time consumption in Section VI-A. Since the amount of plastic credit can slightly change the transaction size of issue and trade, these two transactions are executed 500 times each to get the average transaction size. Note that the vote transaction does not require such a repeated experiment because every vote transaction is only related to one address and one ballot, leading to a fixed data size of the vote transaction. On average, the transaction size (byte) of vote, issue, and trade is 4358, 3266, and 3265, respectively. To estimate the growth trend of transaction size, we assume that 100 producers and

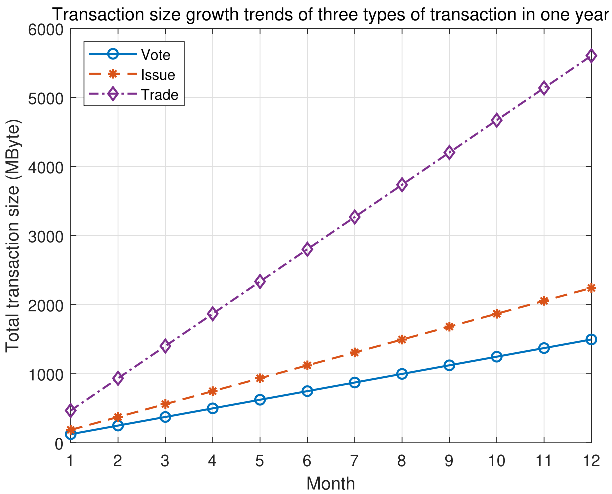

Fig. 6. Transaction size's growth trend consumption of three types of transaction: vote, issue, and trade.

manufacturers are involved in vote, issue, and trade transactions. The number of plastic material RIs to be voted is 10 per day; hence, the vote transaction volume is 1000 per day. The number of each participant's issue and trade transactions is assumed to be 20 and 50 per day, respectively, so the corresponding transaction volumes are 2000 and 5000. Based on the above assumptions, the growth trends of three types of transactions in one year are depicted in Fig. 6.

Compared with vote transaction and issue transaction, the transaction size of trade transaction increases much faster since trade transaction is assumed to be more frequent than the other two types of transactions in the use of the proposed plastic credit system. Based on our estimation, the annual transaction size of the three types of transactions is 1.46, 2.19, and 5.47 GB, respectively. Therefore, the estimated transaction size in total is 9.12 GB per year. Note that there is no compression technique applied in this experiment. Meanwhile, every transaction in the experiment contains a part of function information to describe the functions in the smart contract called "abi," which should appear only once in the first transaction of a smart contract in the practical deployment of the proposed plastic credit system if this smart contract is not modified later. When compression techniques and "abi" information reduction are considered in practice, the total amount of transaction size may be decreased by half.

D. Scalability Discussion

In order to deploy the proposed plastic credit scheme for plastic industry stakeholders, governments, NGOs, and the public to participate, a feasible route is to implement our smart contracts as a decentralized application (DApp) based on the existing blockchain systems. In this case, the scalability of our scheme relies on that of the blockchain base. The core factor impacting the scalability of a blockchain system is the applied consensus mechanism since different consensus mechanisms can result in different performance of tps, block time, transaction fee, etc. Since our scheme is simulated in Ethereum, we analyze two

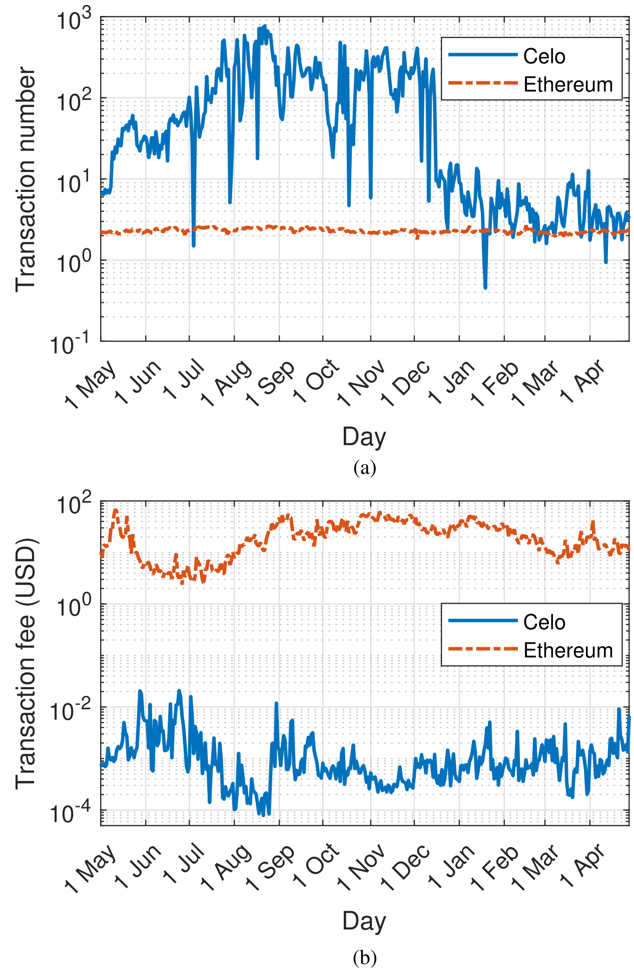

Fig. 7. Comparisons of (a) daily transaction number per address and (b) daily averaged transaction fee between Celo (data source: https://explorer.celo.org/) and Ethereum (data source: https://etherscan.io/charts).

Ethereum-based blockchain systems, Ethereum 1.0 [37] and Celo [38], based on different consensus mechanisms to compare their scalabilities for underpinning our scheme in practice.

Ethereum 1.0 (a.k.a Ethereum) is one of the most prevalent blockchain systems in current implementations based on the consensus mechanism of the proof of work (PoW). The PoW requires all the nodes to contribute their computing power to validate transactions to form the consensus. Owing to the limited computing power and huge network scale, the tps of the current Ethereum 1.0 platform is about 13, and the average block generating time is around 14 s. Celo is another Ethereum implementation based on another consensus mechanism, proof of stake (PoS), which selects validators in proportion to their quantity of stake (e.g., cryptocurrencies) holdings to achieve consensus. Because Celo applies the PoS to avoid time-consuming computation, the tps configured in the current Celo platform is 200, and the averaged block generating time is 5 s. To compare the tps difference, we analyze the daily transaction number per address (active network nodes) of Celo and Ethereum in a recent year from 1 May 2021 to 30 April 2022, as shown in Fig. 7(a). It is clear that a Celo node can handle hundreds or near a thousand transactions per day, but an Ethereum node only validates about two transactions per day on average. The drop of the daily transaction number per address in this year is caused by the sharp decrease of Celo's total transactions, so Celo is far from reaching its tps limit in current.

Furthermore, Celo's transactions cost much less transaction fee than Ethereum's transactions as Celo applies the PoS to get rid of the heavy computation incurred by the PoW in Ethereum for consensus. As shown in Fig. 7(b), while the daily averaged transaction fee to complete a Celo transaction is less than 0.1 USD, an Ethereum transaction can cost about 10 to 100 USD in the recent year with an average cost of 23 USD. Therefore, compared with Ethereum, Celo is a more suitable platform to implement our plastic credit scheme as a DApp in terms of the scalability[3] when more and more plastic companies, governments, and NGOs participate in the scheme to contribute to the plastic recycling and the use of more plastic with higher recyclability.

VII. Conclusion

Relying on a centralized party to determine the so-called agreement for the industry standard is outdated and lacks public trust. In this sense, this article proposes a plastic credit scheme utilizing the decentralized characteristics of blockchain technology to form a plastic governance community. By deploying consortia smart contracts, the plastic credit scheme could determine the plastic recyclability RI according to the latest industry insight and, at the same time, form a voluntary cooperative governance body to monitor the plastic's quality and usage. Furthermore, public infrastructure investors can determine their investments based on the auditing results to support prominent companies and individuals in plastic recycling. As a result, such a plastic credit scheme can incentivize material innovations and provide efficient and powerful means of financing activities that verifiably reduce disposable plastic in the environment to protect our planet.

Further work could involve concrete incentivizing strategies and precautions to prevent potential attacks from malicious internal attacks on the executive voting smart contract. The plastic credit scheme could consider the interoperability of potential over-the-counter plastic credit transactions in the future. Furthermore, additional benefits should also be considered in detail besides government policy being imposed.

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