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RESEARCH ARTICLE

Blockchain-Based Sustainability Index Score for Consumable Products

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ABSTRACT Efforts to combat environmental degradation and tackle climate change have gained significant global recognition. Many advocate that all consumable products should carry sustainability labels to inform consumers about their production methods, resources, and disposal practices. However, the lack of standardized sustainability labels and limited scope of certification bodies pose challenges. Additionally, reported sustainability metrics rely heavily on the transparency and openness of the reporting entities. Therefore, in this paper, we leverage decentralized blockchain technology to transparently document supply chain transactions and sustainability data, cultivating trust among stakeholders and consumers while promoting environmentally friendly practices that lead to a circular economy. Our proposed blockchain-based solution exploits the intrinsic features of the blockchain by building programmable logic of different tailored Key Performance Indicators (KPIs) using smart contracts. In our adaptable system design, KPI scores are used to calculate a product's overall sustainability index score. Our implementation is integrated with the decentralized storage InterPlanetary File System (IPFS) to avoid the high cost of storage on the chain. We present a complete solution with algorithmic details and testing procedures as well as an evaluation of the proposed system accompanied by a cost and security analysis. All of our developed code for smart contracts has been made publicly available on GitHub.

INDEX TERMS Sustainability, index score calculation, transparency, trust, blockchain, Ethereum, smart contracts.

I. INTRODUCTION

According to the United Nations Environmental Program (UNEP), by 2025, urban areas globally are projected to generate 2.2 billion tonnes of waste annually, a staggering increase compared to the 2009 levels, which were less than a third of that amount [1]. As the tide of pollution continues to rise, urgent action is needed to safeguard our environment for future generations. The Ellen MacArthur Foundation's Global Commitment 2023 report on global plastic packaging reveals that the total plastic packaging weight across the market is 142 million metric tonnes, with only 29% being recyclable, while the remaining 71% is composed of non-recyclable plastic [2]. Non-recyclable plastic poses a significant environmental threat, contributing to pollution in various ways [3]. When disposed of improperly, such plastics can persist in the environment for hundreds of years, releasing harmful chemicals and microplastics into ecosystems. These pollutants can contaminate soil, waterways, and marine environments, endangering wildlife and disrupting fragile ecosystems [3].

The Ellen MacArthur Foundation primarily focuses on circular economy, aiming to accelerate the transition to a regenerative economic model [4]. With a significant portion of industries being inactive, business signatories are anticipated to fall short of the crucial 2025 objectives. The world

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is veering off track from achieving the goal of eradicating plastic waste and pollution. Hence, the Foundation forecasts that by 2040, approximately 20 trillion flexible packaging items, including wrappers, pouches, and sachets, will find their way into the ocean [5].

Efforts to combat environmental degradation and tackle climate change have gained significant global recognition, particularly following the establishment of the United Nations Sustainable Development Goals (UNSDG) in 2015. With a target to achieve these goals by 2030, the UNSDG has reinforced the worldwide focus on sustainability, echoing the concerns raised by the Brundtland Report in 1987 [6]. Additionally, the United Nations Framework Convention on Climate Change (UNFCCC) parties held annual meetings to safeguard the ozone layer and stabilize greenhouse gas concentrations in the atmosphere. The Conferences of the Parties (COP) that drifted outcomes and explored new solutions were the Kyoto Protocol of Japan in 1998 and the Paris Agreement of 2015, which aimed to rectify flaws and further improve what the Kyoto Protocol has established [7]. The protocols established at the different COPs are crucial international treaties that play a vital role in addressing climate change by establishing commitments and mechanisms to reduce greenhouse gas emissions and limit global warming, safeguarding the planet's ecosystems, and ensuring a sustainable future for current and future generations.

However, despite persistent collective endeavors to mitigate pollution and diminish greenhouse gas emissions, much remains to be done to ascertain that our actions effectively address these critical environmental issues. Ecological issues arise not just from the disposal of synthetic materials but also from the improper handling of organic waste across the supply chain. Globally, nearly 8 million tons of waste crab, shrimp, and lobster shells, along with 10 million tons of waste oyster, clam, scallop, and mussel shells, are generated annually, often ending up in oceans or landfills, where they impact soils, water bodies, and marine ecosystems [8]. Hence, it is imperative for all companies that produce consumable products to incorporate sustainable practices throughout their supply chain and take responsibility for their production methods.

A cradle-to-cradle life cycle emphasizes customer awareness and advocates for responsible consumption and production. The criteria for identifying sustainable products may vary depending on the nature of the product. It is important to note that while tools exist to assess the sustainability of final products, the sustainability of production facilities is often overlooked. Fortunately, the Facility Environment Module (FEM) of the Higg Index tool 2.0 from the Sustainable Apparel Coalition (SAC) can be utilized to evaluate sustainability scores for fashion apparel. The Higg Index score offers a comprehensive assessment of a fashion product's eco-friendliness, considering the production phase, consumer phase, and end-of-life [9]. Such scoring methodologies have the potential to foster competitiveness among companies and increase consumer awareness. However, their effectiveness relies on the transparency of company owners and their willingness to participate.

A. MOTIVATION

The lack of transparency in sustainability evaluations, audits, and certifications among companies, coupled with the need for standardization in sustainability across consumable products, motivated us to propose a methodology for transparently calculating the sustainability index score of any consumable product. This motivation stems from several factors. Firstly, existing sustainability assessment tools like the Higg Index primarily focus on specific industries or products, such as fashion apparel. While these tools are valuable, they often overlook the broader spectrum of consumable products and fail to provide a universal standard for sustainability assessment. By leveraging blockchain technology, we aim to overcome these limitations and create a comprehensive methodology applicable to all consumable products. Blockchain provides a transparent and immutable ledger that ensures the integrity and traceability of data throughout the entire supply chain [10]. This transparency eliminates greenwashing, builds trust among stakeholders, and enables consumers to make informed decisions based on verified information.

Blockchain enables the creation of smart contracts that can automatically execute predefined criteria for calculating sustainability index scores. These smart contracts can incorporate diverse sets of Key Performance Indicators (KPIs) tailored to different types of consumable products, ensuring flexibility and adaptability to various industries and contexts. By automating the assessment process, blockchain reduces human error and bias, resulting in more objective and reliable sustainability scores.

B. CONTRIBUTIONS

Our proposed methodology harnesses the transformative power of blockchain technology to revolutionize sustainability assessment for consumable products. By providing a transparent, decentralized, and universal framework, it empowers consumers, incentivizes businesses to adopt sustainable practices, and fosters a more environmentally conscious economy. The main contributions of this paper can be summarized as follows:

- We propose a blockchain-based solution that incorporates registration, KPI assessment, and calculation of the sustainability index score for any consumable product.
- We present a blockchain-based design for a transparent method to measure the environmental impact of a consumable product by assessing different KPIs and calculating sustainability index scores on the chain.
- We highlight how our blockchain-based solution can track and trace sustainability audit records, shared reports and calculated sustainability index scores in a trusted, traceable, and transparent manner.
- We present algorithms as well as testing results for registering the participating entities, submitting sustainability

records, providing KPI scores, and calculating sustainability index scores. We make the smart contract code publicly available on GitHub.[1]
- We demonstrate how our solution is not limited to specific consumable products but can be tailored based on sustainability requirements and applications.
- We conduct a thorough evaluation of our solution through comprehensive cost analysis and security assessment.

The rest of the paper is organized as follows. Section II discusses related work from the literature. Section III presents the design details of the proposed blockchain-based solution, followed by the implementation details and algorithms in Section IV. Section V presents the testing details and section VI evaluates the proposed solution and discusses the cost and security analysis. Section VII concludes the paper.

II. RELATED WORKS

In this section, we delve into existing literature that explores the intersection of blockchain technology and sustainability labeling, as well as the calculation of sustainability index scores for products. By reviewing prior research, we aim to gain insights into the various approaches, methodologies, and challenges associated with implementing blockchain-based solutions for sustainability assessment and labeling. Additionally, we seek to identify gaps and opportunities for further advancement in this field.

Sustainability scoring is a versatile concept applicable across various sectors, industries, and products, as evidenced by research efforts. For instance, the work of [11] incorporates developing a sustainability credit score system tailored for the banking industry. Their work highlights the importance of integrating sustainability metrics into financial institutions' practices and decision-making processes. On the other hand, [12] is a review paper that focuses on investigating the most important characteristics that are determinants of evaluating the sustainability of furniture design. Their research identifies ten sustainability characteristics for the environment that they believe would help future furniture designers in creating green and sustainable designs. Similarly, the work of [13] focuses on the sustainability assessment of the furniture industry using a group of indicators. The indicators depend on the activities performed by the company as well as the company size. The sustainability assessment targeted furniture companies in Brazil and helped in identifying gaps for improvement.

Additionally, the authors in [14] shed light on the importance of blockchain-enabled sustainability labeling in the fashion industry. Their work emphasizes the significance of leveraging blockchain's inherent features of transparency, accountability and trust to address sustainability challenges in fashion supply chains.

The study conducted by Gonçalves et al., as described in [6], provides a comprehensive review of sustainability scoring methodologies applied to apparel. The researchers aimed to identify and evaluate various Key Performance Indicators (KPIs) utilized in assessing the environmental impact of apparel while also considering social aspects and the transparency of industry practices in sustainability scoring. Ultimately, the research highlights the need for standardized and transparent approaches to sustainability scoring, facilitating informed decision-making and promoting transparent, sustainable practices throughout the apparel supply chain.

The research of [15] proposes a framework that enables selecting different KPIs systematically to assess the Sustainability Development Goals (SDGs) at a global, national, and corporate level. The SDG performance assessment tool allows users the flexibility to choose the indicators for evaluation. The framework does not use blockchain unlike [16], which utilizes the Hyper Ledger Fabric to trace sustainability along the textile and clothing supply chain. Their focus is on improving the traceability of the clothing supply chain by reducing fabric waste, thereby keeping the consumer informed of the environmental impact of the apparel. At the registration, production, and transportation stages, a score is calculated. At the end, the consumer can view the score and trace the product along the chain. Unfortunately, the score is calculated off the chain every time. Therefore, details on how the score is calculated and what indicators contributed to the score calculation are not mentioned. The paper focuses on tracing the quantities of fabric contributing to the production of each lot of apparel.

The use of blockchain for traceability has also been utilized by [17] for the Environmental, Social, and Governance (ESG) assessment of a company in the textile and apparel industry. In their approach, they have used stochastic multicriteria acceptability analysis and blockchain to evaluate stakeholders' ESG data. Their results demonstrate that the data-driven ESG assessment approach can assess the sustainability efforts of companies and compare their sustainability standing relative to their industry peers.

Sustainability has become increasingly prominent in recent years, yet it continues to evolve in terms of methodologies for measurement and assessment. While current research shows promising results, there remains a gap in transparent methods for calculating the sustainability index score of consumable products. Our blockchain-based solution contributes to the literature by emphasizing the significance of evaluating and assessing the sustainability impact and environmental footprint of consumable products. We introduce various KPIs, KPI scores, and an overall sustainability index score. Our research aims to raise consumer awareness, promote eco-friendly choices, eliminate greenwashing, and foster trust through a transparent framework. Leveraging decentralized disruptive blockchain technology, our system ensures accountability, data integrity, and transparency, serving as the cornerstone of our design.

[1] https://github.com/smartcontract694/SIS/tree/main

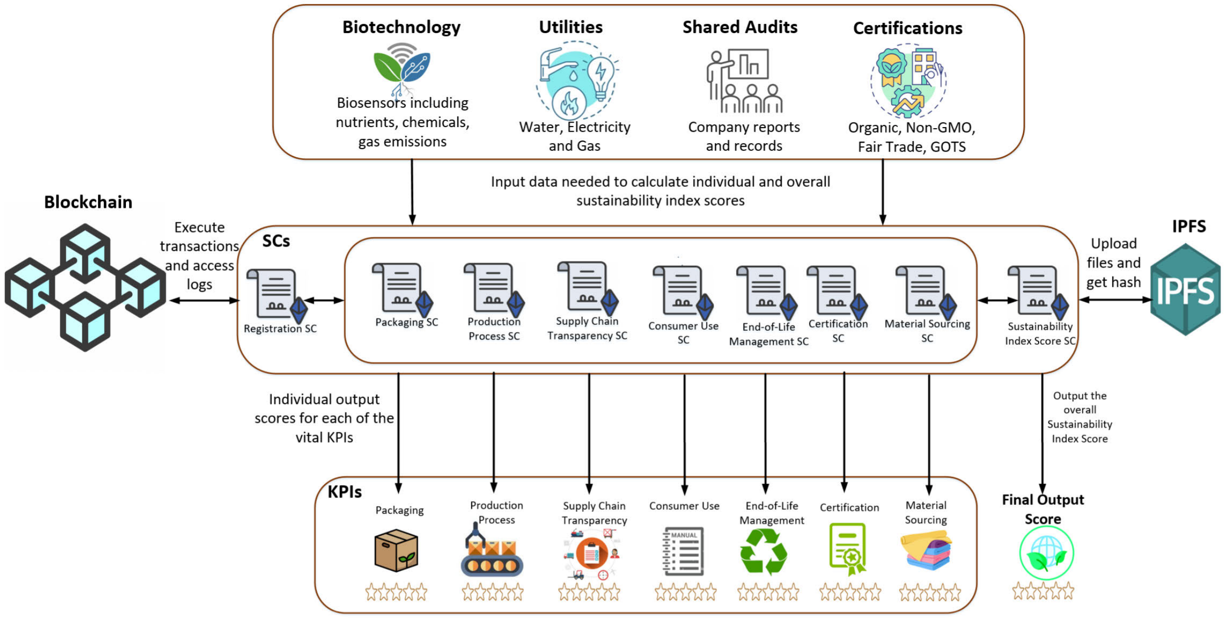

FIGURE 1. System diagram of the proposed blockchain-based solution for the product sustainability index score calculation.

III. SYSTEM DESIGN

In this section, we provide a comprehensive overview of our proposed solution's design, meticulously explaining each component. Our solution, built on blockchain technology, utilizes Key Performance Indicators (KPIs) to evaluate the sustainability of consumable goods. We have carefully selected seven essential KPIs to aid in assessing product sustainability and calculating its Sustainability Index Score (SIS). The SIS serves as a numerical representation of a product's sustainability. However, to instill trust in its value, it must be calculated within a transparent framework that prioritizes trust, accountability, and transparency. Our blockchain-based solution emphasizes these features by utilizing logs, events, and on-chain communications, which are tamper-proof, timestamped, and immutable. The different system components and sequence of events are elaborated in the subsequent subsections.

A. SYSTEM COMPONENTS

Our proposed blockchain system operates on the Ethereum network, employing smart contracts to execute programmable logic. Figure 1 depicts the various components of the system interacting with different smart contracts and communicating with the blockchain network, as well as decentralized storage. The roles of the different components in establishing a SIS are outlined below.

- **Blockchain**: The decentralized Ethereum blockchain serves as the foundation for establishing data provenance, enhancing transparency throughout the process, and fostering trust among interacting entities. It emits events and disseminates notifications for system users, facilitating smoother communication that is timestamped and logged with high data integrity.
- **Participating Entities**: Our solution encompasses several participants that are involved together to effectively calculate the sustainability index score of a consumable product.
  - **KPI managers**: Are registered personnel tasked to monitor the different KPIs and their resource ordering and management. As we have chosen seven different KPIs for our solution, there are consequently seven KPI managers, each manager responsible for a specific KPI smart contract. The KPI managers must be registered to interact with other smart contracts, submit sustainability audit reports, and share KPI sustainability scores.
  - **Sustainability Assurance Firm (SAF)**: Is the entity responsible for providing a sustainability index score for each KPI. It monitors the actions of the KPI managers within their respective smart contracts (SCs). Additionally, the SAF conducts both scheduled and unannounced on-site visits as necessary to fairly assess the sustainability of a product based on each KPI.
  - **Sustainability Assurance Personnel (SAP)**: Works for the SAF and is the owner of all the KPI smart contracts. An agreement is signed off the chain between the SAF and the product owners where it's stored off the chain, and only its hash is available on the chain. Multiple SAPs from the SAF can be involved. SAP also provides individual KPI scores on the chain and owns the KPI smart contracts.
  - **Registration Manager**'': Is the owner of the registration smart contract and the entity responsible for registering other participating entities on the chain.

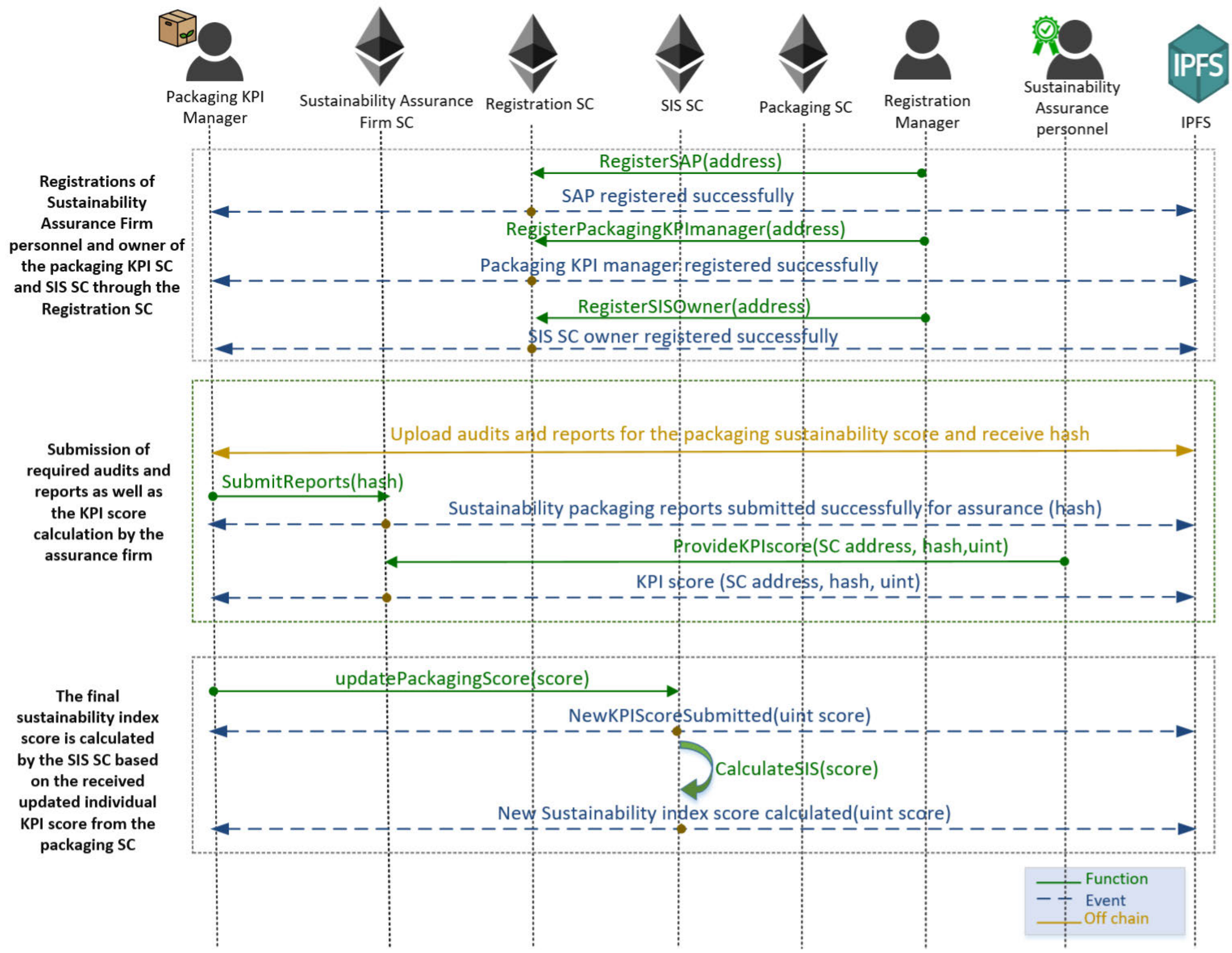

FIGURE 2. Sequence diagram showing the interactions between the packaging KPI manager and other participants.

- **Smart Contracts (SCs)**: The programmable logic executed on the blockchain is determined by the smart contracts. Participating entities agree to the terms and conditions conveyed through these smart contracts and can only interact with executable functions based on their roles and authorizations.
  - **KPI SCs**: Our solution has a dedicated smart contract for each KPI, resulting in seven KPI smart contracts in total. Each KPI smart contract oversees the activities specific to its corresponding KPI. The KPI smart contract is written under the terms agreed upon with the SAF. The owner of the KPI SC is a SAP from the SAF. The hash of the agreement signed between the SAF and the KPI manager is passed as a parameter in the constructor when the SC is deployed.

    Additionally, depending on its nature, each KPI may require input data fetched from off-chain resources. The KPI smart contracts broadcast their data needs and any acquired resources on the blockchain to enable the SAF to assess their sustainability choices better and provide fair sustainability scores. These input data can range from biotechnology resources involving gas emissions and readings from biosensors to utility consumptions such as electricity, water, and gas. Furthermore, it may necessitate the use of information published internally within a company, such as process reports or records and certifications acquired. By incorporating these off-chain data sources, the KPI smart contracts ensure a comprehensive evaluation of sustainability factors, enhancing the accuracy and fairness of the sustainability scores provided by the SAF.
  - **Registration SC**: All participating entities interacting with the SCs are registered through the Registration smart contract (SC), which is owned and managed by the registration manager. The Registration SC maintains a record of all the registered Ethereum Addresses (EAs) and retrieves these records when needed to verify the authorization of an entity.
  - **SAF SC**: The sustainability assurance firm has its own SC where it receives the sustainability reports hashes submitted by the KPI managers and provides KPI sustainability scores. It interacts with

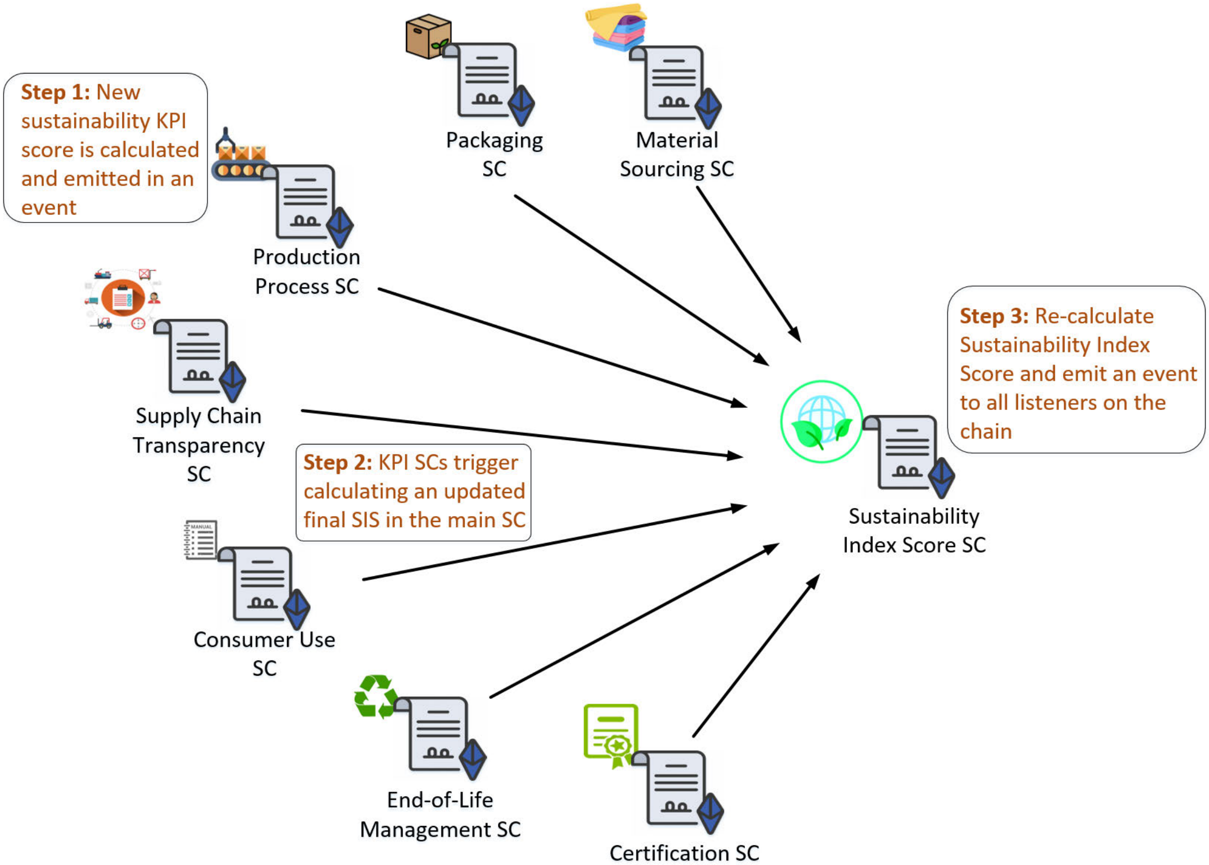

FIGURE 3. A representation of the steps involved in updating individual KPI scores and the recalculation of the final sustainability index score.

sustainability assurance personnel, KPI managers and overseas events and notifications from other SCs

- **SIS SC**: In this smart contract, the sustainability index score for the product is calculated. When the smart contract is deployed, the constructor initializes the individual sustainability scores for each KPI. At any moment, if the score of any individual KPI is updated, the corresponding KPI manager triggers a request in the SIS smart contract to update the KPI score. This action triggers an internal function in the smart contract, which recalculates the sustainability index score of the product.

- **Decentralized Storage**: Our solution uses decentralized storage like the InterPlanetary File System (IPFS) [18], which plays a crucial role in reducing costs associated with storing large amounts of data on the blockchain. By storing data off-chain in a decentralized manner, IPFS enables efficient and cost-effective storage solutions. Instead of storing all data directly on the blockchain, which can be expensive due to the need for every node to store a copy of the entire blockchain, IPFS distributes data across a network of nodes. Decentralized storage solutions like IPFS are essential for scaling blockchain applications while keeping costs manageable and ensuring data availability and integrity.

B. SEQUENCE OF EVENTS

The ultimate goal of our proposed blockchain-based solution is to analyze the sustainability of a product and assess its green effects and adverse effects on the environment. Therefore, our solution offers a transparent method to calculate the sustainability index score of a consumable product. By leveraging blockchain technology and incorporating transparent processes for data collection, analysis, and scoring, we aim to provide stakeholders with clear insights into the environmental impact of the products they consume. This transparency fosters accountability and empowers consumers to make informed choices that align with their sustainability values.

Each consumable product undergoes analysis across seven different KPIs and is assigned an individual KPI score based on onsite visits, assessments, and submitted reports. Figure 2 illustrates the flow of function calls and events between the packaging KPI manager, registration manager, Sustainability Assurance Personnel (SAP), and other smart contracts. Initially, all participating entities are registered by the registration manager. Subsequently, the packaging KPI manager uploads the sustainability report and audits on

TABLE 1. Different KPIs assessed based on different sustainability levels.

	Sustainability Levels				
KPIs	A: Basic Label (1 point)	B: Mid-Level Label (2 points)	C: Advanced Label (3 points)	D: Premium Label (4 points)	E: Elite Label (5 points)
Material Sourcing	Conventional materials (e.g. conventional cotton, polyester)	Some sustainable materials (e.g. recycled polyester, conventional cotton with some organic content)	Majority of sustainable materials (e.g. organic cotton, TENCEL™ lyocell, recycled polyester)	Exclusive use of sustainable materials (e.g. 100% organic cotton, TENCEL™ lyocell, hemp)	Cutting-edge sustainable materials (e.g., bio-based fabrics, regenerative agriculture fibers)
Production Process	Conventional manufacturing (e.g. conventional dyeing, high water consumption)	Some energy and water-saving initiatives (e.g. energy-efficient machinery, water recycling)	Significant energy and water savings (e.g., solar-powered facilities, water-efficient processes)	High energy and water efficiency (e.g., closed-systems)	Carbon-neutral production processes (e.g. renewable energy usage)
Supply Chain Transparency	Limited transparency (e.g., no disclosure of suppliers or manufacturing locations)	Increasing transparency (e.g. some disclosure of suppliers, limited information on labor practices)	Comprehensive transparency (e.g. full disclosure of suppliers, detailed labor practices)	Complete transparency (e.g. full disclosure of suppliers, labor practices)	Supply chain traceability from raw material to finished product
Consumer Use	No guidance on sustainability (e.g., standard care instructions, no emphasis on sustainability)	Basic eco-friendly care (e.g. eco-friendly care instructions, basic tips for garment care)	Comprehensive eco-friendly care (e.g., detailed care instructions, extensive tips for garment care)	Organic care instructions (e.g. care instructions for organic materials)	Sustainable care instructions (e.g., minimal water usage, eco-friendly detergents)
End-of-Life Management	No emphasis on recycling (e.g. no information on recycling, no take-back program)	Limited emphasis on recycling (e.g. some information on recycling, limited take-back program)	Comprehensive recycling emphasis (e.g. detailed information on recycling, active take-back programs)	Detailed recycling focus (e.g. detailed recycling information)	Circular economy practices (e.g. product take-back, recycling initiatives)
Packaging	Non-sustainable packaging materials (e.g., plastic bags, non-recyclable packaging)	Some use of sustainable packaging materials (e.g. recyclable materials, reduced packaging)	Increasing use of sustainable packaging materials (e.g. biodegradable materials, minimal packaging)	Extensive use of sustainable packaging materials (e.g. recycled materials, minimal packaging)	Sustainable packaging (e.g. biodegradable materials, minimal packaging)
Certifications	None	A sustainable certification (e.g. Fair Trade, SA8000)	2 or 3 certifications (e.g. Fair Trade, SA8000, Ethical Trading Initiative (ETI) Base Code, SA8000)	4 or 5 certifications (e.g. GOTS, Fair Trade, Cradle to Cradle, SA8000)	More than 5 certifications (LWG,Fair Trade, Cradle to Cradle, SA8000, GOTS, FSC, SA8000, ETI

IPFS and submits the hash on the chain to the Sustainability Assurance Firm (SAF) smart contract. The SAP assigns a KPI score to the packaging KPI manager based on the submitted reports, on-chain activities, and onsite visits. Finally, the packaging KPI manager updates the packaging KPI score at the Sustainability Index Score (SIS) smart contract. This triggers an internal function in the SIS smart contract to automatically recalculate the SIS of the product and emit an event with the newly calculated score. The SIS SC receives the updated individual sustainability scores from the respective KPI managers. Similarly, the aforementioned process applies for each of the seven KPIs as seen in Figure 3, where every KPI manager is responsible for updating the SIS SC with the updated corresponding KPI score. This would update the final SIS, which helps ensure a comprehensive assessment of the sustainability of the product across all relevant metrics.

At the end of the assessment process, the final sustainability index score is calculated by averaging all of the individual KPI scores. This overall score provides stakeholders with a holistic understanding of the product's sustainability performance across various dimensions, enabling informed decision-making and promoting responsible consumption practices.

C. KEY PERFORMANCE INDICATORS AND SUSTAINABILITY SCORES

In our solution, we have identified seven Key Performance Indicators (KPIs) to serve as our sustainability indicator categories. These seven KPIs are: packaging, material sourcing, supply chain transparency, end-of-life management, production process, consumer use, and certification. Each of these KPIs is assigned an individual score tailored to the specific type of consumable product being assessed. For instance, Table 1 provided is designed for a consumable product that includes fabric and involves manufacturing processes and certifications for ethical sourcing. We aimed to use a diverse example that is flexible enough to accommodate a wide range of consumable products. The consumable product could be a leather or fur item intended for wear or use in various settings, such as home or office environments. The sustainability levels and KPIs outlined in the table can be customized based on specific sustainability requirements.

The material sourcing score is determined based on the type of material used. Conventional materials receive a score of 1, with higher scores awarded for more sustainable materials. Sustainable bio-based fabrics, for example, receive the highest score of 5 and are designated with the elite label. A similar approach is taken with the production process KPI. The sustainability level of the product is influenced by factors such as water and gas usage, as well as emissions generated during production. The use of renewable energy sources such as solar power, along with methods to minimize greenhouse gas emissions, contributes to a higher score. To ensure trust in the sustainability score, supply chain transparency is also evaluated, and a score is assigned for it. Transparency increases with the disclosure of detailed labor practices, resulting in a higher overall score for the product. The consumer-use KPI assesses the instructions provided to consumers for caring for the product. The longevity of the product in the hands of the consumer contributes to its sustainability and results in a higher score. Clear and comprehensive instructions, along with eco-friendly practices, enhance the score further. Encouraging consumers

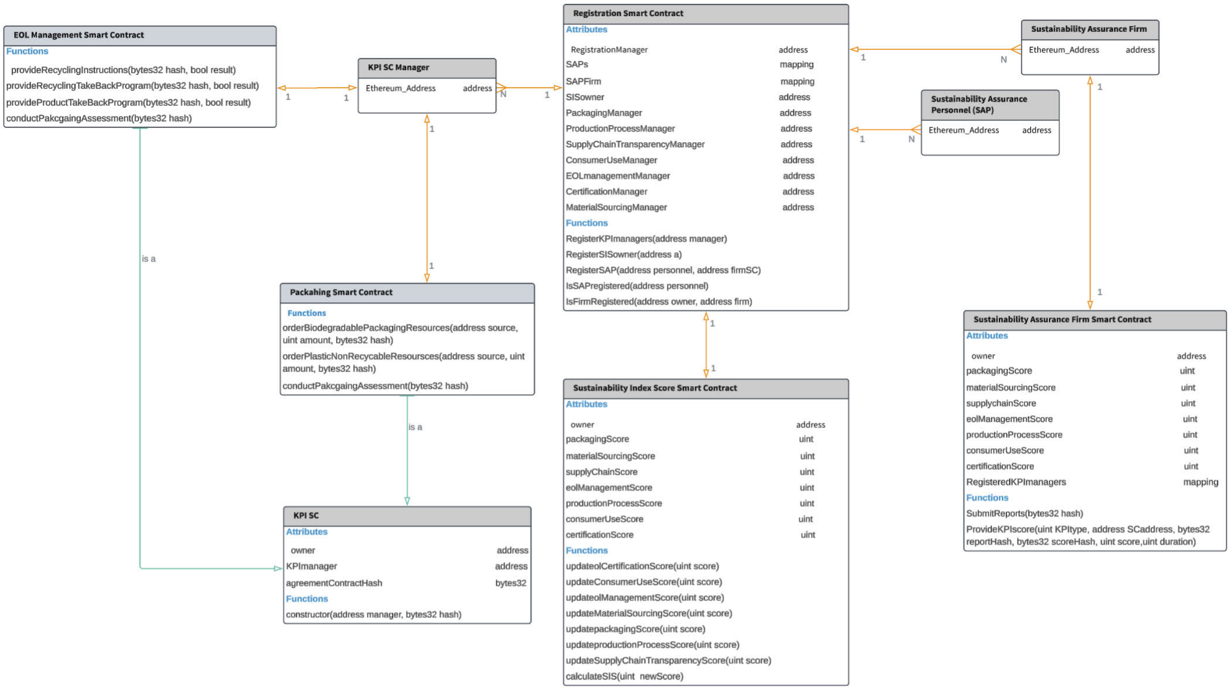

FIGURE 4. Class diagram showing the different smart contracts, functions and attributes in our blockchain solution.

to properly care for and maintain the product not only extends its lifespan but also reduces the need for frequent replacements, thus promoting sustainability.

End-of-life management is a critical KPI that addresses issues concerning a circular economy, recycling, and take-back programs. A cradle-to-cradle lifecycle minimizes waste and maximizes resource efficiency, which promotes leaving an environmental footprint, unlike the traditional cradle-to-grave cycle where items end in disposal eventually. Solutions that facilitate consumers' participation in a circular economy receive the highest score. This includes initiatives such as efficient recycling programs and take-back schemes that enable the reuse or repurposing of materials at the end of a product's life cycle. By promoting circular economy practices, end-of-life management not only minimizes waste but also maximizes resource efficiency, contributing to a more sustainable approach to consumption and production. The packaging KPI promotes the use of biodegradable materials to package the consumable product. The score ranges from 1 to 5, depending on the extent of sustainable packaging utilized.

Additionally, the certification KPI score increases as the product obtains more certifications related to sustainability and ethical fair trade practices. This incentivizes producers to adhere to recognized standards and certifications, thereby ensuring greater transparency and accountability in their operations and supply chains.

Not only can the KPIs be customized based on the consumable product type but also, the five different sustainability levels outlined for each KPI in the table can indeed vary in content based on the specific details and characteristics of the consumable product being assessed. These levels are designed to accommodate a wide range of products and sustainability criteria, allowing for flexibility and customization to suit different contexts and requirements. By tailoring the content of each sustainability level to reflect the unique attributes of the product in question, stakeholders can more accurately assess its sustainability performance and identify areas for improvement.

IV. IMPLEMENTATION DETAILS

The Remix Integrated Development Environment (IDE) is used for the development of the smart contract code as well as its testing [19]. It includes a source code editor, build automation tools, and a debugger integrated into a single graphical user interface. Our framework includes seven KPI smart contracts, a Registration SC, a Sustainability Assurance Firm (SAF) SC, and a Sustainability Index Score (SIS) SC. For each KPI SC, different functions are executed depending on the type and nature of the KPI. In the implementation below, multiple algorithms are detailed, and each algorithm showcases the modifiers used through execution restrictions, the input parameters, and the events emitted.

We have implemented two of the seven KPI SCs. While each KPI smart contract shares a similar design, they are tailored to accommodate the unique characteristics and requirements of each KPI type and its intended usage. This modular approach ensures consistency in design while allowing flexibility to adapt to specific KPI needs and functionalities. Figure 4 shows a class diagram that provides a visual representation of the structure and relationships between the smart contracts. Attributes define the properties or characteristics of SCs, while methods encapsulate the operations or behaviors that SCs can perform. Several KPI SC managers are registered in the Registration SC. The Packaging SC as well as the EOL Management SC are KPI SCs. It can also be seen that several SAP can be associated with a single SAF and SAF SC.

All participating entities must be registered through the registration smart contract (SC). Registration ensures accountability and authorization using predefined roles. Registered EAs are authorized to execute function calls based on their role. The subsequent section provides a detailed explanation of the algorithms employed in the smart contracts. Each algorithm specifies particular input parameters, conditions and restrictions.

A. REGISTRATION OF KPI MANAGERS

In our implementation, there are seven KPIs. Each KPI is managed using a separate SC. A KPI manager who manages the respective KPI SC must be authorized to do so. Hence, the EA must be registered using the function *RegisterKPImanager* of the Registration SC. Algorithm 1 shows the details of registering a KPI manager. The function takes an EA, and the type of KPI as input parameters. The function validates the caller's identity to ensure that only the Registration SC owner, who is also the registration manager, is authorized to execute the function. The KPI type is given a number from 1 to 7 to ease the comparison and reduce costs of execution. This helps in eliminating the need of strings as the comparison involves a single integer. Depending on the number stored in the KPI variable, the different KPI manager variables are initialized. An error is displayed if the value falls outside the accepted range or if the EA does not correspond to the EA of the registration manager.

Algorithm 1 Registration of KPI Managers

```
Input : caller, user, RegistrationManager, KPI
caller holds the Ethereum Address of the function caller
user holds the Ethereum Address of the user that needs to be registered
KPI holds a character to show which KPI is the address for
if caller == RegistrationManager then
    if KPI == 1 then
        eolManagement = user
    if KPI == 2 then
        certification = user
    if KPI == 3 then
        consumerUse = user
    if KPI == 4 then
        materialSourcing = user
    if KPI == 5 then
        supplychainTransparency = user
    if KPI == 6 then
        packaging = user
    if KPI == 7 then
        productionProcess = user
    else
        Show an error. KPI must be between 0 and 8.
else
    Preview an error and return the contract to the previous state.
```

B. REGISTRATION OF A SAP

A sustainability assurance personnel (SAP) working at the sustainability assurance firm (SAF) must be registered in order to execute the required function. Algorithm 2 provides the details of registering an SAP using the Registration SC. The EA of the firm, as well as SAP, are passed as parameters to the function. A modifier is used to ensure that only the registration manager performs the registration. A mapping is used to associate registered SAPs with a 'true' boolean. The registered SAP is also stored in another mapping with the EA of the firm.

Algorithm 2 Registration of a SAP

```
Input : caller, personnel, RegistrationManager, firm
personnel holds the EA of the SAP
firm holds the EA of the sustainability firm the SAP is associated with
SAPs mapping that holds all registered SAPs
SAPFirm mapping that holds the EA of the firm for each SAP
if caller == RegistrationManager then
    SAPs[personnel] = true
    SAPFirm[personnel] = firmSC
else
    Preview an error and return the contract to the previous state.
```

C. SUBMISSION OF SUSTAINABILITY REPORTS

Sustainability reports and audits are submitted according to agreed-upon deadlines and requirements. KPI managers provide the IPFS hash of the prepared documentation to the SAF SC for assessment. Algorithm 3 below shows the details of the submission of reports by the KPI managers. Firstly, the EA of the caller is checked to verify that it is registered as a KPI manager. Then an event is emitted with the IPFS hash, and EA of the KPI manager announcing the successful submission of the reports.

D. PROVISION OF KPI SCORES

For each KPI, a score is determined based on the provided audits and assessments as well as on-site visits. The score is provided by the SAF SC. Hence, the caller of the function must be the owner of the SC and should be a registered SAP from a registered SAF. The score is then provided for one of the seven KPIs. The score is based on an assessment

Algorithm 3 Submission of Sustainability Reports

Input : caller, KPImanagers, RegistrationSC, hash
KPImanagers holds the EAs of all registered KPI managers
hash a bytes32 variable that holds the IPFS hash
if *caller* ∈ *KPImanagers* **then**
  Emit an event to announce the sustainability reports have been submitted successfully with the *hash*
else
  Preview an error and return the contract to the previous state.

report and supporting documents. Therefore the IPFS hash of the report is also included as an argument in the function. Algorithm 4 shows the details of the function. At the end of the algorithm, an event is emitted broadcasting the new KPI score, KPI name, the associated KPI SC along with the time stamp, validity duration and a report hash as well as a score hash. The hashes correspond to files stored on the decentralized IPFS.

E. KPI SCORE UPDATE

When a score is provided by the SAP for a KPI, the respective KPI manager provides an update in the SIS SC which triggers the calculation of a new overall SIS. Algorithm 5 present the details of the process. The caller of the function must be a registered KPI manager otherwise an error is shown and the state of the contract is reverted. After receiving the new score as a parameter for the specific updated KPI, the algorithm updates the respective KPI score, emits an event *NewKPIScoreSubmitted* notifying all listeners of the newly received KPI score and then using an internal function *calculateSIS* calculates the new total score. The score is calculated by adding all the seven individual KPI scores. The sum is then multiplied by 10 before its divided by 7. This is done to avoid errors from integer division, as floats do not exist in Solidity. The integer that is formed at the end must be divided by 10 off the chain to get the intended SIS. The final SIS is emitted as an event along with the calculated sum.

F. PACKAGING ORDERING AND ASSESSMENT

Each KPI is governed by an individualized smart contract, housing activities directly linked to its objectives. This structured approach fosters transparency by delineating a clear operational framework for each KPI, enabling the SAF to make informed assessments. Additionally, this setup empowers the SAF to deliver overall sustainability scores based on the performance of each KPI. The packaging SC incorporates various functions, each representing an order executed by the KPI manager. Upon each order request, an event is emitted to notify all listeners of the activity, including on-site visits. The quantity and type of orders, in conjunction with on-site visits, contribute significantly to determining the score of

Algorithm 4 Provision of KPI Scores

Input : caller, SAP,owner, RegistrationSC, KPI, reportHash, scoreHash, score, validity
SAP an EA of the owner of the SAF SC
owner EA of SAF SC owner
KPI variable to identify which KPI the score is for
reportHash report IPFS hash
scoreHash score IPFs hash
reg SC address of RegistrationSC
if $caller == owner \wedge (SAP \in reg.SAPs) \wedge (SAF \in reg.SAFirm)$ **then**
  if $KPI == 1$ **then**
    eolManagementScore = score
  if $KPI == 2$ **then**
    certificationScore = score
  if $KPI == 3$ **then**
    consumerUseScore = score
  if $KPI == 4$ **then**
    materialSourcingScore = score
  if $KPI == 5$ **then**
    supplychainTransparencyScore = score
  if $KPI == 6$ **then**
    packagingScore = score
  if $KPI == 7$ **then**
    productionProcessScore = score
  else
    Show an error. KPI must be between 0 and 8.
    Revert contract to previous state.
  Emit an event announcing the new KPI *score* using the KPI, KPISCaddress, reportHash, scoreHash, block.timestamp, validity
else
  Preview an error and return the contract to the previous state.

the packaging KPI. Algorithm 6 shows the different order requests, including biodegradable packaging, recyclable packaging, and plastic non-recyclable packaging, as well as all events emitted. The algorithm also shows an event with an IPFS hash emitted that includes the packaging assessment results.

G. EOL MANAGEMENT AND ASSESSMENT

Similarly, the End-of-Life (EOL) management SC oversees all activities related to product end-of-life and sustainability choices. Algorithm 7 outlines various functions detailing the types of end-of-life instructions and programs offered to customers, such as recycling instructions, recycling take-back programs, maintenance, and product take-back programs. An assessment of the EOL methodologies is also performed and the result is emitted on the chain in an event that includes the IPFS hash. The availability of these functions on the blockchain facilitates a trusted and transparent sustainability assessment.

Algorithm 5 KPI Score Update

Input : caller, KPImanagers, RegistrationSC, score
KPImanagers holds the EAs of all registered KPI managers
score new KPI score
if *caller* ∈ *KPImanagers* **then**
    KPIscore = *score*
    Emit an event to announce that new KPI score is available by the KPImanager
    totalSum = packagingScore + materialSourcingScore + supplychainScore + eolManagementScore + productionProcessScore + consumerUseScore + certificationScore
    $totalSum = totalSum * 10$
    $finalScore = totalSum/7$
    Emit an event to announce New Calculated SIS using the (caller, totalSum, finalScore)
else
    Preview an error and return the contract to the previous state.

Algorithm 6 Packaging Ordering and Assessment

Input : caller, PackagingManager
PackagingManager holds the EA of packaging SC manager
score new KPI score
if *caller* == *PackagingManager* **then**
    ▷ Order Biodegradable packaging
    Emit an event announcing the Biodegradable packaging *sourceSCaddress*, *amount*, *orderHash*
    ▷ Order Recyclable packaging
    Emit an event announcing the Recyclable packaging *sourceSCaddress*, *amount*, *orderHash*
    ▷ Order Plastic Non-Recyclable Resources
    Emit an event announcing the Non-Recyclable *sourceSCaddress*, *amount*, *orderHash*
    ▷ Conduct Packaging Assessment
    Emit an event announcing the Assessment Details *hash*
else
    Preview an error and return the contract to the previous state.

V. TESTING AND VALIDATION

The implemented smart contracts underwent rigorous testing using the Remix IDE. In this section, we present the testing results following the successful execution of the functions. It's worth noting that our functions can only run successfully if they are called by authorized entities. For our testing scenario, we registered the Packaging SC manager and the EOL management SC manager to demonstrate how the KPI managers interact with the smart contracts. Table 2 provides the Ethereum addresses utilized in the testing process.

Algorithm 7 EOL Management and Assessment

Input : caller, EOLManager
EOLManager holds the EA of EOLmanagement SC manager
score new KPI score
if *caller* == *EOLManager* **then**
    ▷ Provide Recycling Instructions
    Emit an event providing recycling instructions *hash*, *resultBoolean*
    ▷ Provide Recycling Take Back Program
    Emit an event announcing the recycling take back program details *hash*, *resultBoolean*
    ▷ Provide Product Maintenance
    Emit an event announcing the product maintenance details *hash*, *resultBoolean*
    ▷ Provide Product Take Back Program
    Emit an event announcing the product take back program details *hash*, *resultBoolean*
    ▷ Conduct EOL Assessment
    Emit an event announcing the Assessment Details *hash*
else
    Preview an error and return the contract to the previous state.

TABLE 2. Ethereum addresses of the system users.

Name	Ethereum Addresses
SAP	0x4B20993Bc481177ec7E8f571ceCaE8A9e22C02db
SAF	0x9ecEA68DE55F316B702f27eE389D10C2EE0dde84
Packaging Manager	0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2
SIS SC Owner	0x78731D3Ca6b7E34aC0F824c42a7cC18A495cabaB
Registration Manager	0x5B38Da6a701c568545dCfcB03FcB875f56beddC4
EOL SC Manager	0x617F2E2fD72FD9D5503197092aC168c91465E7f2

A. REGISTRATION OF KPI MANAGERS

KPI managers must be registered by the registration manager to be able to interact with the smart contracts, submit reports and manage their own KPI SCs. Figure 5 shows the successful registration of the packaging KPI manager. In the figure, the 'from' address represents the Ethereum address of the registration manager responsible for initiating the registration process. The input data includes two parameters: the Ethereum address (EA) of the KPI manager and the KPI type, which is specified as '6', indicating the packaging KPI manager. Similarly, the registration of the other KPI managers was successful, affirming the effective implementation of Algorithm 1.

B. REGISTRATION OF A SAP

All KPI smart contracts are owned by a Sustainability Assurance Personnel (SAP) from the sustainability assurance firm. The logs presented in Figure 6 indicate the successful registration of a SAP. For the testing of the registration of a

FIGURE 5. Logs showing the successful registration of a KPI manager.

SAP, two addresses are provided as required by Algorithm 2: the first input parameter represents the address of the SAP, while the second one represents the address of the firm SC.

FIGURE 6. Logs of the successful registration of the SAP.

C. SUBMISSION OF SUSTAINABILITY REPORTS

In our testing scenario, the registered Packaging KPI manager has successfully submitted the IPFS hash to the firm using the SAF smart contract. The logs displayed in Figure 7 include the address of the KPI manager, the IPFS hash, and the timestamp of the submission. The logs display the output emitted in an event following the successful execution of Algorithm 3 which is used by KPI managers to submit the IPFS hash of the reports.

FIGURE 7. Logs showing a KPI manager submitting the sustainability report IPFS hash.

D. PROVISION OF KPI SCORES

The SAF evaluates the submitted reports and employs its own strategies, including on-site visits and log tracing, to generate a KPI score for the KPI managers. In our testing scenario, the SAP successfully executes Algorithm 4 and assigns a sustainability score of '4' as an individual sustainability score for the packaging KPI. Figure 8 displays the results and logs emitted after providing the KPI score, including the score, IPFS hash, the report hash, and the timestamps of issue and expiry.

FIGURE 8. Logs of successfully providing a KPI score from the SAF SC.

E. KPI SCORE UPDATE

The SIS smart contract always maintains a record of the latest individual score for each KPI. If the KPI managers receive an updated score, they update the SIS smart contract accordingly. Figure 9 displays the individual KPI scores for all seven KPIs, where 'p', 'm', 's', 'e', 'pp', 'co', and 'ce' represent packaging, material sourcing, supply chain transparency, end-of-life management, production process, consumer use, and certification, respectively. The total sum is 26 off the chain and 260 on the chain, with the SIS being 37 on the chain and 3.7 off the chain. However, after successfully executing Algorithm 5 and entering the new score for the packaging KPI as '3', the SIS smart contract computes a new sum and recalculates the SIS. Figure 10 illustrates the newly updated scores, where the total sum is computed to be 250 on the chain, and the final SIS is 35 on the chain and 3.5 off the chain. This demonstrates the correct logical execution of the algorithms. Moreover, Figure 10 also shows two events emitted, where the top event shows the new KPI score emitted and the bottom event shows the results of the calculations performed by the SIS SC.

FIGURE 9. Logs indicating initial individual sustainability KPI scores.

F. PACKAGING SC AND EOL MANAGEMENT SC

For each KPI there is a SC owned by a SAP from the SAF but managed by a registered KPI manager. To demonstrate the successful testing of the KPI SCs, Figure 11 showcases the events emitted from the successful ordering of biodegradable packaging resources. The KPI SCs ensure transparency of all activities performed by the KPI managers and enable the SAF

FIGURE 10. Logs showing the events emitted after successfully updating an individual KPI score and the recalculation of the SIS.

to stay updated with all activities on the chain. Consequently, the SAF can provide fair and accurate sustainability scores for each KPI. Similarly, the EOL Management SC functions were successfully tested, and the events were emitted as expected, affirming that the code works as intended.

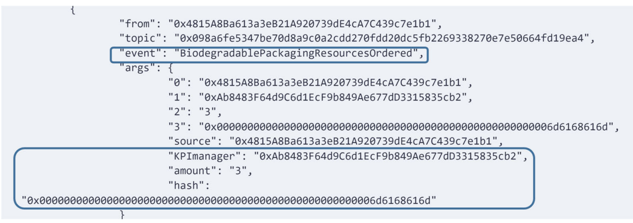

FIGURE 11. Events emitted after successfully ordering biodegradable resources by the packaging KPI manager.

VI. DISCUSSION

In this section, we evaluate our solution by conducting a cost and security analysis and explore its potential applications in other contexts.

A. COST ANALYSIS

In our cost assessment of implementing our blockchain-based solution, we acknowledge the potential expenses associated with leveraging blockchain technology. While blockchain offers advantages like transparency and immutability, it also introduces costs such as transaction fees and infrastructure maintenance. Our analysis focuses on measuring the transaction cost incurred by each executed function of the smart contracts.

In Ethereum, transactions and smart contract execution are measured in gas, a unit representing computational effort. Each operation or computational step within a smart contract requires a specific amount of gas, and users pay for this gas using Ether (ETH), the native cryptocurrency of the Ethereum network.

Gas is priced in Gwei, which is the smallest denomination of Ether, equivalent to 0.000000001 ETH. The gas price, denoted in Gwei, determines the cost per unit of gas consumed during transaction processing. Tables 3, 4, 5, and 6 provide insights into the transaction costs associated with each function in the implemented smart contracts. These costs are calculated both in Ether and USD. The calculations are based on an average gas price of 7 Gwei, which was observed on April 30th, 2024, with 1 Ether equivalent to 3187 USD. It is important to note that Ethereum's transaction fees can vary significantly due to fluctuations in Ethereum's price and network congestion. The costliest operation among the functions listed in Table 3 amounts to approximately 1.5 USD. Similarly, in Table 4, the highest incurred cost totals around 1.17 USD, while in Table 5, it stands at 0.6 USD. Lastly, in Table 6, the most expensive operation reaches approximately 0.58 USD. The higher costs correlate with operations involving the manipulation of mappings and mathematical computations. It is expected that functions requiring more computational resources would result in higher transaction costs. While the calculated transaction costs are reasonable considering the computational resources utilized on the Ethereum network, there are alternative blockchain networks that offer competitive and cost-efficient transaction fees.

For instance, networks like Cardano and zkSync provide lower transaction costs compared to Ethereum. The price of zkSync's native token and Cardano's native token are significantly lower than Ethereum's, with zkSync's token priced at 0.0412 USD and Cardano's token priced at 0.455 USD. As depicted in the tables, utilizing zkSync and Cardano for transaction execution results in reduced transaction costs. This highlights the potential cost savings and efficiency gains that can be achieved by exploring alternative blockchain networks for executing smart contract functions.

B. SECURITY ANALYSIS

Security analysis is essential in the development of Solidity code as it prevents exploitation and breaches from malicious actors, ensures reliability, and maintains trust. Smart contract vulnerabilities can be exploited by attackers, causing contract failures and the loss of user funds. Therefore, we analyzed our smart contract code using Slither, a static analysis framework for Solidity smart contracts. It helps identify potential security vulnerabilities and coding errors. Our five implemented smart contracts were analyzed by Slither, and the code was improved based on the tool's output results. We have ensured that all assigned Ethereum addresses are not equivalent to zero in our code before they are assigned to other variables. This has eliminated the previously reported low issues. The code had optimization and informational issues reported related to naming conventions and unused variables, which we made sure that they were altered where necessary. Figure 12 shows the results from our Slither security analysis where no low, medium, or high issues were reported. This ensures our code is free from security vulnerabilities and follows best practices in Solidity development. Additionally, the continuous improvement of our code based on the output results of security analysis tools reinforces our proactive approach to security and ensures that our smart contracts adhere to the highest standards of quality and integrity.

TABLE 3. Transaction costs of the registration smart contract functions.

Function Name	Transaction Gas	Transaction Fee (Ether)	Cost with Ethereum (USD)	Cost with Cardano (USD)	Cost with zkSync (USD)
registerKPImanager()	46783	0.000327	1.04	0.00015	0.000013
registerSAP()	69246	0.000485	1.54	0.00022	0.000020
registerSISowner()	46288	0.000324	1.03	0.00015	0.000013
isSAPregistered()	24175	0.000169	0.54	0.000077	0.000007
isFirmRegistered()	24827	0.000174	0.55	0.00079	0.0000072

TABLE 4. Transaction costs of the SIS and SAF smart contracts functions.

Function Name	Transaction Gas	Transaction Fee (Ether)	Cost with Ethereum (USD)	Cost with Cardano (USD)	Cost with zkSync (USD)
submitReports()	34959	0.000245	0.78	0.00011	0.000010
provideKPIscore()	60006	0.00042	1.34	0.00019	0.000017
updatePackagingScore()	52543	0.000368	1.17	0.00017	0.000015
updateConsumerUseScore()	52432	0.000367	1.17	0.00017	0.000015
updateEOLmanagementScore()	52521	0.000368	1.17	0.00017	0.000015
updateMaterialSourcingScore()	49610	0.000347	1.11	0.00016	0.000014
updateCertificationScore()	52410	0.000367	1.17	0.00017	0.000015
updateProductionProcessScore()	52411	0.000367	1.17	0.00017	0.000015
updateSupplyChainTransparencyScore()	49656	0.000348	1.11	0.00016	0.000014

TABLE 5. Transaction costs of the packaging KPI smart contract functions.

Function Name	Transaction Gas	Transaction Fee (Ether)	Cost with Ethereum (USD)	Cost with Cardano (USD)	Cost with zkSync (USD)
conductPackaging()	25404	0.0001778	0.567	0.0000809	0.00000733
orderBiodegreadable()	27093	0.0001897	0.604	0.0000863	0.00000781
orderPlasticNonrecyclable()	27115	0.0001898	0.605	0.0000864	0.00000782
orderRecyclable()	27137	0.0001900	0.605	0.0000864	0.00000783

TABLE 6. Transaction costs of the EOL management KPI smart contract functions.

Function Name	Transaction Gas	Transaction Fee (Ether)	Cost with Ethereum (USD)	Cost with Cardano (USD)	Cost with zkSync (USD)
conductEOLassessment()	25794	0.000181	0.575	0.0000822	0.00000744
provideProductMaintenance()	26049	0.000182	0.581	0.0000830	0.00000751
provideProductTakeBackProgram()	25993	0.000182	0.580	0.0000828	0.00000750
provideRecyclingInstructions()	26093	0.000183	0.582	0.0000831	0.00000753
provideRecyclingTakeBackProgram()	26027	0.000182	0.581	0.0000829	0.00000751

```
INFO:Printers:
Compiled with solc
Number of lines: 403 (+ 0 in dependencies, + 0 in tests)
Number of assembly lines: 0
Number of contracts: 5 (+ 0 in dependencies, + 0 tests)

Number of optimization issues: 0
Number of informational issues: 0
Number of low issues: 0
Number of medium issues: 0
Number of high issues: 0

+-------------+-------------+------+------------+--------------+----------+
|     Name    | # functions | ERCS | ERC20 info | Complex code | Features |
+-------------+-------------+------+------------+--------------+----------+
| Registration |     6      |      |            |     Yes      |          |
|     SAF     |      3      |      |            |     Yes      |          |
|     SIS     |      9      |      |            |      No      |          |
|  Packaging  |      5      |      |            |      No      |          |
| EOLmanagement |    6      |      |            |      No      |          |
+-------------+-------------+------+------------+--------------+----------+
INFO:Slither:registration.sol analyzed (5 contracts)
```

FIGURE 12. Slither analysis results.

C. COMPARISON WITH OTHER SOLUTIONS

Table 7 presents a comparison between our solution and existing work in the literature. Papers [6], [14], and [15] are non-blockchain based solutions, where the first one is a review paper that showcases the effect of using blockchain for sustainability labelling in the fashion industry. The paper does not go through methods of calculating a sustainability score or a KPI score. Additionally, the review paper [6] also concentrates on the clothing industry, but unlike [14], it uses different sustainability levels identified based on predetermined KPIs. The authors of [15] focused on finding the SDG and on selecting KPIs tailored for both global and national corporate contexts. The other two solutions presented in [16] and [17] are blockchain-based solutions where one calculates the sustainability score for the textile off the chain while the other calculates the ESG score using ESG data. In contrast, our presented approach offers a more comprehensive solution.It is a versatile blockchain-based framework that can be tailored to analyze the sustainability of any consumable product, providing both the sustainability index score and KPI scores for each identified KPI. These KPIs are customized to suit the specific product type and project scope. Notably, the solution emphasizes transparency

TABLE 7. Comparison with existing work in the literature.

	Target	Blockchain-based	Sustainability Score Calculation	KPI Scores	Description
[14]	Fashion Industry	False	False	False	Review paper on the effect of blockchain sustainability labeling for the fashion industry.
[6]	Clothing Industry	False	Sustainability labels	KPI identification	Review paper on sustainability labeling and scoring for the fashion industry.
[15]	Global and national corporate level	False	SDG	KPI selection only	A framework that enables selecting different indicators to assess the SDGs at a global and national corporate level.
[16]	Textile and clothing supply chain	True	calculated off-chain	False	A framework implemented for the traceability of textile in the clothing supply chain to reduce the waste of fabric.
[17]	Textile and apparel industry	True	ESG score	ESG data	The ESG is determined using stochastic multicriteria acceptability analysis.
Our solution	Consumable products	True	True	True	Developed a trusted blockchain-based solution that transparently determines sustainability KPIs, KPI scores, and a overall sustainability index score for consumable products

by recording all calculations and scores on the blockchain, ensuring visibility and accountability. Additionally, it introduces five distinct sustainability levels, ranging from basic to elite, to enable a more nuanced evaluation of sustainability across different products and industries.

D. GENERALIZATION

Our blockchain-based solution integrates various sustainability Key Performance Indicators (KPIs) to thoroughly evaluate the sustainability of consumable products and generate an overall sustainability index score. While our implementation incorporates seven distinct KPIs, our design is flexible and can accommodate additional or fewer KPIs based on specific application requirements. Moreover, each KPI can be assessed across different elite levels, providing granularity in sustainability evaluation. Although our approach currently assigns scores ranging from 1 to 5 for each KPI, this scoring system can be adjusted to include more or fewer variations as needed. As a result, our solution is versatile and adaptable, making it suitable for diverse applications and enabling the analysis of sustainability across various product types.

E. CHALLENGES AND LIMITATIONS

Although blockchain promises prominent benefits from increasing efficiency, enhancing trust, and reducing intermediaries, it still presents a few challenges and hurdles.

- **Scalability**: Handling large volumes of data from multiple stakeholders simultaneously at the same time requires advanced planning. This is crucial to ensure the blockchain network can handle the expected transaction load within a specific time frame. The right throughput and processing speed must be tested and scaled for. Implementing scalability solutions such as sharding, sidechains, or layer-2 protocols can help increase the throughput and processing speed of the blockchain network [20]. These solutions enable parallel processing of transactions, allowing the network to handle higher transaction volumes.
- **Interoperability**: Lack of interoperability between different blockchain platforms and systems may hinder seamless data exchange and collaboration among stakeholders in the supply chain. Improving standardization and encouraging collaborations can promote interoperability.
- **Data Accessibility**: Access to relevant sustainability data from all product lifecycle stages may be limited. Without comprehensive data, the sustainability index score may not accurately reflect the product's environmental impact. Incentives can serve as a motivational tool to encourage participants to prioritize transparency when sharing sustainability information.
- **Data Accuracy and Reliability**: The accuracy and reliability of data acquired and stored on the blockchain depend on the integrity of the input sources. If the data sources are inaccurate or unreliable, it can lead to incorrect sustainability assessments. Hence, verifying that the input sources are accountable for their data and endorsed by reputable entities is crucial.

VII. CONCLUSION

In this paper, we have proposed, designed, implemented, and evaluated a blockchain-based solution for assessing the sustainability of consumable products. Our design incorporates various consumable product requirements, customizing Key Performance Indicators (KPIs) and their sustainability levels and scores. An aggregate transparent sustainability index score is computed based on these KPI scores. Our solution enhances environmental awareness for consumers and stakeholders, fosters trust using immutable on-chain data records, and encompasses accountability through certification authorities and tamper-proof logs. Security and cost analyses demonstrate the feasibility of our solution. It was shown that updating the sustainability index score of a product incurs the highest cost, primarily due to the need to update an individual KPI score and recalculate the sustainability index score. We have also compared our solution against existing work in the literature and showed how our blockchain solution, unlike the other solutions, is used to find the sustainability KPI scores and a holistic sustainability index score for a consumable product. The scores are all available on the chain, exploiting the programmable logic of smart contracts. As a future work, our proposed solution can integrate different categories of KPIs to investigate further the effect of social, ecological, and ethical KPIs on the final overall score of a consumable product.

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