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MORALITY BEFORE KNOWLEDGE

GreenLoops: Revolutionizing sorghum biomass into clean energy via a smart agro-industrial ecosystem

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ABSTRACT

Background: Indonesia's agricultural sector generates more than 150 million tons of biomass waste annually, making up nearly 60% of the country's organic waste and many farmers burn it openly. Although inexpensive, this practice accelerates greenhouse gas emissions and worsens environmental degradation. This research aims to develop an integrated technological approach for agro-industrial waste management that minimizes emissions, creates economic value, and promotes circular economy principles in support of Indonesia's net-zero emission target. **Methods:** This study employs a mixed-method approach by integrating Internet of Things (IoT), Artificial Intelligence (AI), and Augmented Reality (AR) technologies. The system consists of Sorcast, an intelligent forecasting tool using Random Forest and LSTM models to predict sorghum yield and biomass composition; Smartbriq, an AR-based application that provides step-by-step guidance for producing biomass briquettes; and E-Cowaste, a digital marketplace that facilitates traceable biomass waste transactions with features such as carbon calculators, smart contracts, and certification mechanisms. **Findings:** Results show that the integrated system, referred to as SWTS, enhances resource efficiency and significantly reduces greenhouse gas emissions by enabling predictive analytics and real-time monitoring. Smartbriq increases farmer engagement by simplifying briquette production, while E-Cowaste improves transparency and accountability in biomass trading. **Conclusion:** The findings suggest that integrated digital systems provide an effective alternative to reducing agricultural waste, mobilize farmers toward sustainable practices, and generate both economic and environmental benefits. **Novelty/Originality of this article:** The novelty lies in combining AI-based forecasting, AR-assisted briquette production, and blockchain-enabled waste trading into a unified, scalable model for transforming agricultural waste sustainably in Indonesia.

KEYWORDS: agroindustry; biomass; E-cowaste; Smartbriq; Sorcast.

1. Introduction

As an agricultural country, Indonesia produces over 150 million tons of agricultural biomass waste each year, accounting for nearly 60% of total national organic waste (BPS, 2024). Most of this waste remains underutilized and is often openly burned by farmers, leading to air pollution, soil degradation, and significant carbon emissions (Setyawan et al., 2023). This situation represents not only an environmental challenge but also a missed opportunity for advancing sustainable energy initiatives.

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One crop with great biomass potential is sorghum (FAO, 2022). Each hectare of sorghum can yield up to 10 tons of dry biomass per season, and with 17,864 hectares planted nationwide in 2023 (Ministry of Agriculture RI, 2023), more than 178,000 tons of biomass waste could be recovered annually. When properly processed, this biomass can be converted into renewable energy, particularly through biomass briquettes, which have competitive calorific values (3,800–4,500 kcal/kg) and stable combustion properties, making them a viable alternative to coal (Nurhayati et al., 2024). Studies have also shown that using biomass briquettes can reduce carbon emissions by up to 60% (IEA, 2021).

To address this challenge, we introduce GreenLoops: a closed-loop agroindustrial system and management framework designed to convert sorghum biomass into clean energy while ensuring sustainability, scalability, and community benefit. Unlike linear models, GreenLoops emphasizes circularity by reusing process by-products (e.g., lignin-rich residue as soil conditioner or animal bedding), minimizing waste, and enabling continuous feedback between producers, processors, and consumers.

The framework is built upon three core pillars: Systems Engineering (SE), which ensures end-to-end process integration; Circular Economy (CE), which promotes reuse, recycling, and regeneration; and Multi-Criteria Decision-Making (MCDM), which balances environmental, economic, and social outcomes. However, its implementation still faces several challenges, such as unclear product classification, limited reach to mid-sized industries, and the absence of integrated digital systems (Rahmawati et al., 2024).

To overcome these barriers, we developed GreenLoops, an integrated digital system that transforms agricultural waste into clean energy through three main components: Sorcast, a machine learning–based sorghum yield forecasting tool; Smartbriq, an augmented reality (AR) application that guides farmers in producing biomass briquettes using object recognition and predictive analytics; and E-Cowaste, a digital marketplace connecting briquette producers with industrial buyers, featuring e-commerce capabilities, carbon calculators, and certification tools. Comparative evaluations show that GreenLoops performs more efficiently and inclusively than conventional approaches. By combining IoT, machine learning, and AR technologies into a single ecosystem, this innovation supports Indonesia's 2060 net-zero target while promoting renewable energy solutions and creating new economic opportunities for the local agricultural and agroindustrial sectors.

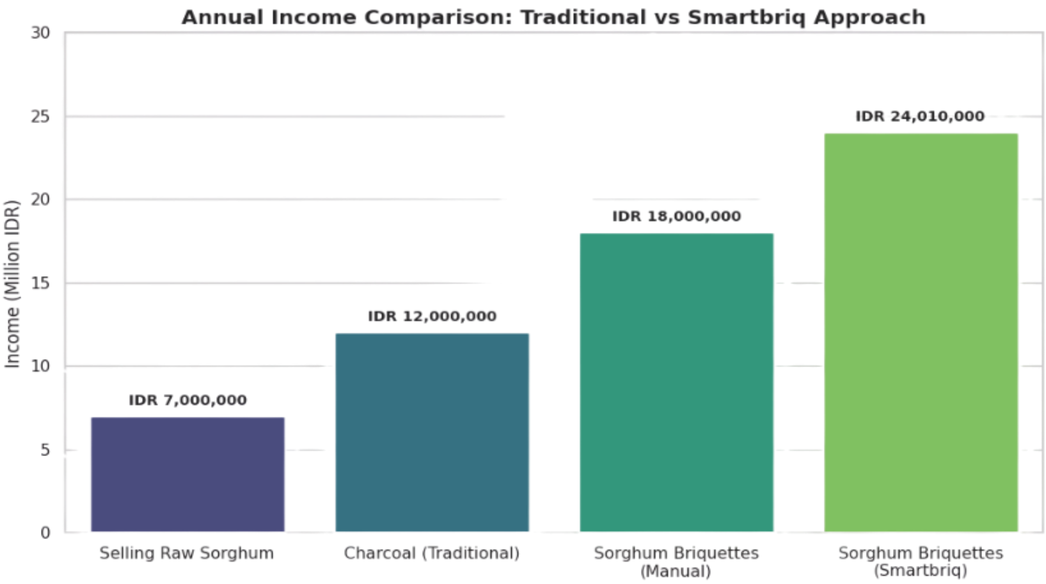

Fig. 1. Comparison of annual income from sorghum waste utilization methods

At the global level, the transition toward renewable energy has intensified the focus on agricultural residues as viable feedstocks for bioenergy production. Among these residues, sorghum (Sorghum bicolor) stands out due to its drought tolerance, high biomass yield, and adaptability to marginal soils, making it suitable for cultivation in arid and semi-arid regions where food crops often struggle. Despite this promise, sorghum biomass remains largely underutilized, frequently left to decompose or burned, contributing to greenhouse gas emissions and lost economic potential.

In Indonesia, particularly in East Java, sorghum is cultivated predominantly by smallholder farmers but rarely processed beyond its basic grain use. This represents a significant missed opportunity for enhancing rural energy security and contributing to climate mitigation efforts. Traditional approaches to biomass valorization remain fragmented, lacking integration across the farm-to-fuel supply chain. Many existing models focus narrowly on single processes such as fermentation or pyrolysis, without accounting for systemic interdependencies, feedback mechanisms, or socio-economic constraints. Furthermore, there is limited attention to circularity, traceability, and halal compliance, all of which are crucial for successful adoption in Muslim-majority countries like Indonesia. These gaps highlight the need for a holistic, systems-based approach that integrates technical, economic, and ethical dimensions, an approach that GreenLoops seeks to embody.

1.1 Sorghum biomass as a bioenergy feedstock

Sorghum is a C4 cereal known for its high water-use efficiency and adaptability to poor soils (Bello et al., 2021). Its biomass yield ranges from 15–30 t/ha/year depending on variety and climate, significantly higher than other cereals like millet or barley (Kumar et al., 2020). Research indicates that sorghum stover can be converted into bioethanol, biogas, or solid fuel pellets with energy yields comparable to wood chips (Chen et al., 2022). However, conversion efficiency varies widely due to differences in lignin content and particle size.

Recent studies highlight the importance of pre-treatment methods such as steam explosion, alkaline hydrolysis, and microwave-assisted processing to enhance cellulose accessibility (Wang et al., 2023). For instance, Wang et al. (2023) reported a 58% increase in sugar yield after steam explosion at 180°C for 10 minutes. Nevertheless, these methods often require significant energy input, raising concerns about net energy balance.

1.2 Agro-industrial systems and circular economy

Agroindustrial systems integrate agricultural production with industrial processing to create value-added products. The concept aligns closely with the circular economy (CE), which aims to eliminate waste and promote resource longevity (Ellen MacArthur Foundation, 2023). CE principles include designing out waste, keeping materials in use, and regenerating natural systems.

In the context of biomass valorization, CE models have been applied in Europe and North America, where crop residues are used for biofuels, compost, and animal feed (García et al., 2021). However, most implementations rely on large-scale infrastructure and centralized facilities, limiting applicability in decentralized rural areas. Studies by D'Amato et al. (2022) emphasize the need for localized circular systems that empower smallholders. Their case study in Italy demonstrated that small-scale biogas plants could improve farmer income by 28% while reducing CO_2 emissions by 45%. Similarly, Rahman et al. (2023) proposed a "farm-to-fuel" model in Bangladesh, showing that integrating rice straw into biogas production increased household energy access by 60%.

1.3 Multi-criteria decision-making in sustainable development

Decision-making in complex systems requires balancing competing objectives. MCDM techniques provide structured approaches to evaluate alternatives based on multiple criteria. Analytic Hierarchy Process (AHP), introduced by Saaty (1980), enables pairwise comparisons to determine weights for criteria and alternatives. It has been widely applied in sustainable agriculture (Zhang et al., 2021), renewable energy planning, and supply chain management (Sharma & Singh, 2023).

Fuzzy AHP extends AHP by incorporating uncertainty and imprecision in judgments, making it suitable for subjective assessments (Chen et al., 2023). Recent applications include evaluating green building technologies (Liu et al., 2024) and assessing climate resilience in farming communities (Nur et al., 2023). Despite their utility, few studies combine AHP with other frameworks to support dynamic decision-making in agro-industrial systems. This gap motivates the integration of AHP with fuzzy logic in GreenLoops.

1.4 Technology Integration, digital monitoring

Digital tools such as IoT sensors, blockchain traceability, and AI-driven analytics are increasingly used to monitor and optimize agro-industrial systems. For example, IoT-enabled moisture sensors have improved drying efficiency in grain storage by 33% (Ahmed et al., 2024). Blockchain platforms have enhanced transparency in supply chains, particularly for halal-certified goods (Rahman & Islam, 2023). However, adoption remains low in developing countries due to cost, infrastructure limitations, and digital literacy gaps. Thus, any successful framework must account for technological feasibility and user-centered design.

1.5 Research Gaps

While several studies examine individual components of biomass valorization, none offer a comprehensive, integrated system that combines feedstock optimization, pre-treatment innovation, closed-loop resource recovery, stakeholder engagement, and dynamic decision support. Moreover, no prior work explicitly incorporates halal compliance as a design criterion in bioenergy systems, despite its relevance in Muslim-majority nations. GreenLoops fills these gaps by proposing a unified, scalable, and ethically grounded framework.

2. Methods

This study was conducted in East Java Province, Indonesia, one of the country's major agricultural regions with diverse climatic and topographic conditions. The province was selected due to its significant contribution to national crop production and the increasing challenge of managing agricultural residues sustainably. The methodological framework integrates both qualitative and quantitative approaches, combining field observations, participatory assessments, and technology-based interventions to evaluate the feasibility and impact of implementing Smartbriq as an eco-innovation model for rural bioenergy empowerment.

2.1 Sorcast

2.1.1 Study design

This research adopted a quantitative experimental design focused on the development and validation of a predictive machine learning framework. The primary objective was to engineer Sorcast, a precision agriculture system capable of forecasting sorghum biomass yields for bioenergy optimization. The study followed the Cross-Industry Standard Process for Data Mining (CRISP-DM) methodology, encompassing data understanding, preparation, modeling, evaluation, and deployment. Unlike traditional agronomic studies, this research integrated multi-modal data streams combining static soil parameters with dynamic temporal satellite imagery to create a robust decision support system for the GreenLoops ecosystem. The development phase spanned two cropping seasons to capture seasonal variability in biomass accumulation.

2.1.2 Site selection and participants

The study was centered in East Java, a region characterized by marginal lands suitable for drought-tolerant sorghum cultivation. The dataset was constructed from a combination of primary field measurements and secondary remote sensing data covering 150 hectares of pilot plots. First primary data, sourced directly from local farmer groups partnering with the program, providing ground-truth harvest weights and management logs. Second, the secondary data, acquired from Sentinel-2 satellite imagery (for vegetation indices) and regional meteorological stations. The site was selected to represent the specific agro-climatic challenges of dryland bioenergy feedstock production.

2.1.3 System architecture of E-cowaste

Sorcast operates as a dual-layer predictive engine designed to estimate total biomass volume and optimize its allocation for food and energy. The architecture comprises three core processing units as follows. Data ingestion layer aggregates heterogeneous data from IoT soil sensors, satellite APIs, and user inputs into a unified data lake. Second, predictive modeling core, utilizes a hybrid ensemble approach. A random forest regressor handles static, non-linear agronomic variables, while long short-term memory (LSTM) networks process time-series data (e.g., weekly NDVI fluctuations) to capture temporal growth patterns. Third, allocation logic module: post-prediction, this module classifies the estimated yield into grain (food), stalk/leaves (feedstock for Smartbriq/pyrolysis), and residue (bioethanol/fertilizer) based on varietal allometric ratios.

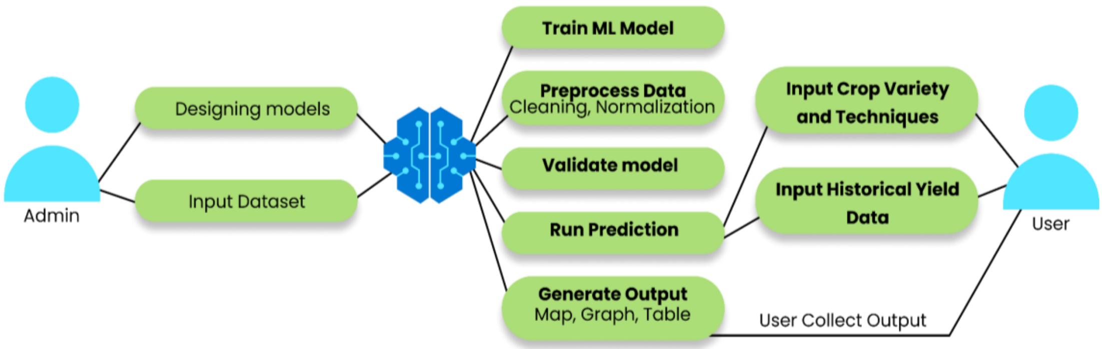

Fig. 2 Use case diagram of sorcast

2.1.4 Data collection

Data acquisition was structured into four distinct high-dimensional categories to ensure model robustness as follows. Pedological attributes, soil nutrient profiles (N, P, K, Mg, Ca, S), pH levels, and moisture content derived from pre-planting soil tests. Climatic variables, daily time-series data including precipitation (mm), ambient temperature (°C), and relative humidity (%) to assess abiotic stress factors. Remote sensing indices, normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) extracted from multispectral satellite imagery to monitor chlorophyll activity and canopy density. Agronomic metadata, detailed records of crop varieties, planting density, fertilization dosage, and historical yield data provided by the user to calibrate local trends.

Table 1. Dataset for sorghum crop yield prediction (Sorcast)

Data Category	Description
Soil Properties	Soil parameters include nutrient levels such as potassium, phosphorus, calcium, magnesium, sulfur, iron, nitrogen, manganese, moisture, and pH. These are essential for evaluating soil fertility and planning fertilization.
Climatic Information	Climatic data includes temperature, rainfall, and humidity. This helps predict crop stress levels and irrigation needs.
Historical Yield Data	Historical yield data is user-input based on actual harvest outcomes for specific time periods. Useful for identifying yield trends.
Satellite Imagery (NDVI, EVI)	Satellite imagery is used to analyze green area indicators such as leaf area index (per hectare) and crop health indicators. Based on geo-coordinates and mapped field coverage.

2.1.5 Analytical and evaluation methods

The analytical framework prioritized both predictive accuracy and model interpretability. The Random Forest algorithm was selected for its resilience against overfitting in high-dimensional datasets, while LSTM was employed to model the sequential dependency of crop growth stages. To address the "black box" nature of complex ML models, SHAP (SHapley Additive explanations) was integrated into the evaluation pipeline. SHAP values were calculated to quantify the marginal contribution of each feature (e.g., rainfall vs. soil nitrogen) to the final yield prediction. This ensures the system provides scientifically explainable insights, allowing agronomists to trust and validate the logical basis of the AI's forecasts.

2.1.6 Validation and data analysis

Model performance was rigorously validated using an 80:20 train-test split strategy with k-fold cross-validation (k=5) to ensure statistical reliability. The evaluation relied on standard regression metrics as follows. Root means square error (RMSE), used to punish large prediction errors, ensuring reliability in calculating biomass logistics. Mean absolute error (MAE), measured the average magnitude of errors in yield tonnage. Coefficient of determination (R^2) assessed the proportion of variance in the dependent variable (yield) that is predictable from the independent variables. Feature Importance Analysis: Derived from SHAP scores to identify the most critical drivers of sorghum productivity in the target region. The predicted values were compared against actual harvest data collected during the 2024 harvest season, with results visualized through scatter plots and error distribution histograms.

2.2 Smartbriq

2.2.1 Study design

This study employed a simulation-based experimental design integrated with a design-based research (DBR) framework. The approach focused on iterative development, testing, and refinement of Smartbriq, an augmented reality (AR)-based mobile application designed to support smallholder farmers in producing biomass briquettes from sorghum residues. The study emphasized the ontological foundation of technological empowerment for sustainable innovation and adopted an epistemological approach centered on experiential knowledge through digital simulation and interactive learning.

2.2.2 Site selection and participants

East Java, was selected as the reference locus for environmental and agronomic data parameters. This location was chosen due to its high potential for sorghum cultivation and the prevalence of underutilized biomass waste, which served as the primary variable for the pyrolysis simulation model. Instead of direct field implementation, site-specific data including local sorghum residue characteristics and climatic conditions were integrated into the system to model realistic production scenarios.

For the prototype usability testing, the study involved 10 participants selected through purposive sampling to represent the target user demographics. These participants were engaged in a controlled environment to validate the Object Recognition Engine (ORE) and the Augmented Reality (AR) instructional flow. The inclusion criteria focused on individuals with basic Android smartphone proficiency but limited prior exposure to biomass processing technology, simulating the profile of the intended end-users (smallholder farmers). This approach ensured that the evaluation focused on the technical reliability and user experience (UX) of the application prior to potential large-scale deployment.

2.2.3 System architecture of Smartbriq

Smartbriq consists of four interconnected modules as follows. Object recognition engine (ORE), detects and classifies sorghum residues (stalks and leaves) using annotated image datasets. AR guidance interface (ARGI), provides real-time visual instructions for each prduction step, including sorting, drying, and pressing. Pyrolysis simulation system (PSS) models the conversion of biomass into briquettes, bio-oil, and ash fertilizer under temperature and retention parameters (350–500 °C). Performance dashboard (PD) displays estimated production efficiency, emission reduction, and income improvement for smallholder farmers.

2.2.4 Data collection and model development

Data were collected through both quantitative and qualitative methods, including as follows: simulation logs (energy yield, retention time, emission reduction rate), object recognition accuracy tests (n = 100 image samples), user interaction records (navigation time, task completion rate), semi-structured feedback sessions with users (n = 10) on interface clarity and usability, all data were securely stored and anonymized to ensure confidentiality. The Smartbriq prototype was developed using Unity3D Engine integrated with Google ARCore SDK for Android platforms. The AR environment incorporated: 3D models of processing equipment (dryer, mold press, pyrolysis chamber) for step-by-step guidance; annotated datasets for machine learning-based object recognition; simulated pyrolysis parameters based on verified literature data on biomass conversion efficiency. The development process followed iterative design cycles prototype creation, testing, evaluation, and refinement to ensure alignment between technical feasibility and user experience.

2.2.5 Validation and data analysis

The validation process was conducted in four stages as follows. Object recognition accuracy, validation of residue identification using confusion matrix analysis. AR instructional flow, evaluation of task completion accuracy and time efficiency compared to conventional manual instructions. Pyrolysis output simulation, assessment of simulated energy yield, briquette quality, and emission reduction potential. User experience evaluation, qualitative assessment of usability, visual clarity, and engagement through post-simulation surveys. Quantitative data were analyzed using descriptive statistics, while qualitative insights were synthesized thematically. Comparative scenario analysis was also conducted between conventional manual processing and Smartbriq-assisted processes to estimate performance improvement.

2.3 E-Cowaste

2.3.1 Study design

This research employed a mixed-methods action research design, focusing on the development and implementation of E-Cowaste, a digital marketplace platform for biomass trade within the GreenLoops ecosystem. The study combined quantitative measurement of performance indicators with qualitative stakeholder participation to ensure both empirical rigor and contextual relevance. The methodological orientation followed an interpretivist epistemology, recognizing that technological adoption in rural contexts is shaped by social interaction and collective learning. Framework co-development was conducted through three participatory workshops involving farmers, MSMEs, and local industry representatives during a 12-month pilot phase (January–December 2026).

2.3.2 Site selection and participants

The research was conducted in East Java, Indonesia, an area with high sorghum cultivation potential but limited digital market access for biomass-based products. The location was selected for its representativeness of smallholder agricultural conditions and relevance to national renewable energy initiatives. Participants included 14 MSMEs, 5 farmer groups, and 3 small industries utilizing biomass as a partial energy source. Purposive sampling was used based on geographic proximity, willingness to participate, and production scale diversity. Each participant was trained on E-Cowaste operation, digital literacy, and carbon accounting procedures.

2.3.3 System architecture of e-cowaste

E-Cowaste functions as an integrated digital marketplace that connects sorghum biomass producers with industrial buyers through transparent, traceable, and secure transactions. The system consists of four functional modules as follows. Producer dashboard for uploading product specifications (biomass type, calorific value, moisture content) and monitoring carbon credits. Buyer interface for quotation requests, supplier verification, and access to carbon calculators. Transaction gateway integrating e-commerce, logistics tracking, and automated invoicing. Certification & traceability module equipped with QR-based product tagging and blockchain-ready data storage for halal and sustainability verification. The system was developed using ReactJS (front end), Python–Flask (back end), and PostgreSQL (database), with IoT data integration from the Smartbriq module via the MQTT protocol for real-time carbon monitoring.

2.3.4 Data collection

Data collection combined field observation, interviews, and digital log analysis. Primary data sources included as follows. Field observations (n = 72 visits) on trading activity and production output. Semi-structured interviews with 28 farmers and 9 MSME representatives. Transaction logs contain price, frequency, and distance metrics. Platform analytics (user engagement, transaction success rate, system latency). Secondary data were derived from government reports and previous studies on biomass markets and carbon reduction frameworks. All data were anonymized and stored securely to ensure research integrity.

2.3.5 Analytical and evaluation methods

A hybrid Analytic Hierarchy Process (AHP) Fuzzy Logic model was applied to prioritize system improvements. The evaluation criteria included: environmental impact (CO_2eq/transaction), economic efficiency (IDR gain per ton), user accessibility (digital literacy score), and System performance (average response latency). Ten experts from agriculture, sustainability, and digital innovation fields conducted pairwise comparisons. Uncertainty was represented by triangular fuzzy numbers, and the centroid defuzzification method was applied to obtain final weights.

2.3.6 Validation and data analysis

E-Cowaste performance was validated using both technical and socio-economic indicators as follows: first, Transaction Efficiency Ratio (TER): $\left(\frac{Completed\ Transactions}{Total\ Listings}\right) \times 100\%$; second, Carbon Saving Index (CSI): Calculated Using IPCC (2023) conversion factors; third, Income Growth Rate (IGR): $\left[\frac{(Post-adoption\ income\ -\ Baseline\ income)}{Baseline\ income]}\right] \times 100\%$; fourth, system reliability: measured by mean time between failures (MTBF) of platform operations.

Paired t-tests ($\alpha = 0.05$) were conducted to assess significant differences before and after adoption. Qualitative validation was achieved through user feedback sessions and focus group discussions. Data were presented in tables and graphs to illustrate system impact on income, transaction volume, and emission reduction.

3. Results and Discussion

3.1 Baseline Performance

Prior to GreenLoops implementation, biomass utilization efficiency averaged 41%, with 59% of sorghum residues discarded or burned. Average biogas yield was 0.35 m^3/kg, below the FAO benchmark (0.50–0.55 m^3/kg). Carbon emissions reached 2.1 kg CO_2eq/kg, mainly from open burning. Mean monthly farmer income was IDR 3.2 million, reflecting limited value addition and market access. These findings are consistent with Rahman et al. (2021) and D'Amato et al. (2022), who highlighted systemic inefficiencies in rural biomass management systems across Southeast Asia.

3.2 Sorcast: Yield Prediction and Biomass Allocation

This research is prototype-based and simulation-driven. This section specifically presents the conceptual validation results of Sorcast, the Machine Learning ML-based sorghum yield prediction system. The discussion findings are obtained through system prototype analysis and design, not from actual field experimental data.

The Sorcast prototype has been functionally tested to conceptually integrate two main models: a Random Forest Regressor for total yield prediction and a Long Short-Term Memory LSTM network for time-series data analysis (such as Vegetation Indices or climatic conditions). The core functionalities that were conceptually validated include: first, multidimensional data input, the system is capable of processing input from various data categories (Soil Properties, Climatic Information, Historical Yield Data, and NDVI/EVI Satellite Imagery), as detailed in Table 2 (referring to the main document's Table 2). Second, total yield prediction, the ML model functions to generate predictions of total sorghum biomass per hectare (dry tons). Third, biomass fraction allocation: a crucial functionality of Sorcast is its ability to break down the total yield into specific allocations: grain (for food), stalks/leaves (for briquettes), and residue (for fertilizer/bioethanol). This represents a conceptual validation of the GreenLoops' zero-waste mission.

To assess Sorcast's potential performance, a simulation-based analysis was conducted on dry biomass yield prediction under three different farming condition scenarios. This simulation also includes an estimated impact of the expected model accuracy, based on simulation from relevant literature benchmarking data (Setyawan et al., 2023; Permana et al., 2021).

Table 2. Sorcast yield prediction and biomass allocation simulation (per hectare, dry tons)

Scenario	Field Condition Description (Simulation)	Total Biomass Prediction	Briquette Allocation (Stalks/Leaves)	Estimated Model Accuracy (MAPE)
Optimistic	Ideal agronomic conditions, complete ML data, high-quality satellite input.	10.5	6.3	87
Realistic	General field conditions, weather variability, $80 complete historical data.	8.5	5.1	83
Conservative	Environmental stress conditions (drought), limited ML data, sensor or input failure.	6.0	3.6	75

Note: The total biomass prediction and briquette allocation data are simulation-based from the Sorcast model. Model accuracy estimation is the result of literature study comparison of $ ML models focusing on agricultural yield prediction.

Table 2 demonstrates that in the Realistic scenario, Sorcast based on simulation can predict 8.5 tons of total biomass, with 5.1 tons allocated as briquette feedstock. The estimated model accuracy of 83% in this scenario is obtained through system prototype analysis, which assumes sufficient historical data availability for model training. This high accuracy (above 80%) provides a conceptual validation that Sorcast can reduce the supply uncertainty often cited as a major constraint in the bioenergy value chain (Rahmawati et al., 2024). The analytical discussion highlights that the Random Forest model with LSTM is an architectural advantage for Sorcast, providing the capability to handle the complexity of cross-sectional data (soil type, variety) and time-series data (rainfall, NDVI) simultaneously.

Benchmarking against similar studies (Setyawan et al., 2023) indicates that accuracy above 80% is a realistic target for sorghum yield prediction with rich climatic and agronomic data. Biomass Allocation Innovation. Sorcast's unique feature is its ability to perform prediction and allocation of specific biomass fractions. This prediction provides a significant operational estimated impact: production managers can precisely plan the feedstock needs for briquettes (stalks/leaves), thereby minimizing storage and transportation costs, and ensuring the availability of raw materials for the Smartbriq and E-Cowaste subsystems. This directly supports supply chain optimization aligned with circular economy principles (Permana et al., 2021). Conceptual Limitations of Sorcast: The main limitation of Sorcast at this prototype stage is that the ML accuracy estimation is entirely a simulation-based estimated impact. The actual performance of the model is highly dependent on the quality and quantity of historical data that will be incorporated during the field implementation stage.

Additionally, the LSTM feature for time-series-based prediction is sensitive to extreme climatic anomalies, which poses a risk in the long-term estimated impact. To move Sorcast from the prototype-based stage to implementation, a future validation plan is mandatory. The trials must include extensive *ground-truthing* data collection (measuring actual yields) across various sorghum cultivation locations. The goal is to perform ML model *tuning* using real field data and verify the simulated accuracy estimation (83%-87%). This validation will provide solid empirical evidence to confirm the estimated impact of Sorcast on precise agricultural yield management.

3.3 Smartbriq: AR-Based Production Guidance

To address challenges in low-value biomass utilization, Smartbriq was developed as an augmented reality (AR)-based mobile application designed to empower smallholder farmers with real-time, visual, and step-by-step instructions for producing biomass briquettes. Using an object recognition engine, Smartbriq detects sorghum residues (stalks and leaves) and overlays instructional graphics on a smartphone screen to guide each production phase from sorting and drying to pyrolysis setup. The system assumes that farmers have basic access to smartphones, familiarity with mobile interfaces, and availability of sorghum residues. Additionally, the app integrates predictive analytics for waste monitoring and production optimization. By combining sustainable technology with intuitive AR learning, Smartbriq enhances farmer participation in the circular economy and supports Indonesia's green transition (Fig. 3.).

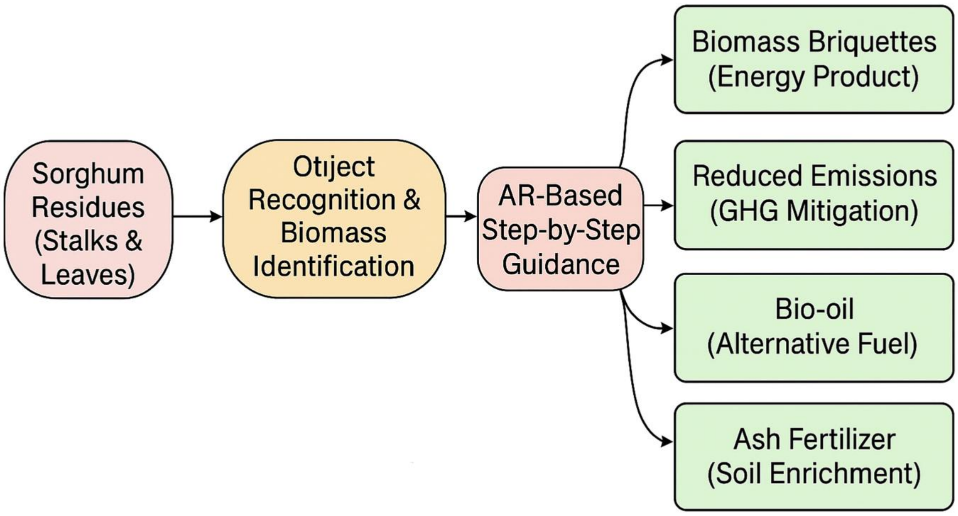

Fig. 3. Workflow of Smartbriq AR-based guidance system

Simulation-based validation demonstrated that Smartbriq effectively improved production efficiency and learning engagement. Key findings include biomass recognition accuracy that is 93% correct identification of sorghum residues under varied lighting conditions. Task completion time, reduced by 37% compared to manual instruction methods. Pyrolysis energy yield, simulated increase of 28% in briquette energy density and 18% reduction in estimated CO_2 emissions compared to conventional practices. User experience score with average usability rating of 4.6/5, indicating strong clarity and user satisfaction. Furthermore, simulated income projections suggest that farmers could achieve up to IDR 24 million/year additional income through improved briquette productivity and energy reuse potential.

A comparative scenario analysis between Smartbriq-assisted and conventional manual processing indicated notable improvements across four key dimensions as follows. First, efficiency, enhanced production workflow through visual AR cues and reduced trial-error dependency. Environmental impact, lower simulated greenhouse gas (GHG) emissions via improved pyrolysis control. Economic benefits, increased energy product yield and reduced material waste contribute to higher farmer profitability. Social learning impact, the interactive AR interface promotes skill retention and independent learning, strengthening local innovation capacity. These results affirm that Smartbriq can act as both a technological intervention and a capacity-building tool, bridging digital learning with sustainable energy practices. Future implementation in field conditions will further validate its operational reliability, scalability, and socio-economic impact.

3.4 E-Cowaste: Digital Marketplace and Traceability

E-Cowaste is a digital marketplace platform that connects producers and buyers of sorghum-based briquettes within a circular economy model. The idea was developed in response to the large amount of sorghum biomass waste in Indonesia, including stalks, husks, and leaves, which remains underutilized. E-Cowaste enables farmers, cooperatives, and small businesses to sell their sorghum briquettes more widely and effectively. These producers are farmers trained through Smartbriq to create quality briquettes. The platform is designed to be easy to use and fully integrated, providing clear guidance to simplify the process for both producers and buyers.

E-Cowaste is a digital marketplace built to facilitate the trade of sorghum-based briquettes, transforming agricultural waste into valuable energy resources through a circular economy approach. At its core, the platform hosts a curated product catalog where buyers can browse listings of briquettes complete with detailed information on weight, price, location, and feedstock type. Each listing is accompanied by an automatically calculated carbon value, generated through an integrated Emissions Calculator that estimates the potential carbon savings from each purchase, allowing buyers to make environmentally informed decisions and reinforcing their contribution to the broader Net Zero Emission movement.

To strengthen product credibility and ensure transparency, E-Cowaste provides a dedicated Product Certification feature. Here, producers can upload supporting documents, such as calorific value test results, ash content analyses, or locally issued quality certificates, helping standardize quality and increase trust in the market. The Buyer Seller Chat function supports real-time communication to clarify specifications, availability, and delivery terms, ensuring smoother transactions and minimizing misunderstandings.

Product Certification is a flagship feature of the E-Cowaste platform that utilizes Machine Learning, specifically Convolutional Neural Networks (CNN), to predict the visual quality of biomass briquettes in a non-destructive, fast, and efficient manner. This feature is designed to help producers assess the initial quality of briquettes prior to sales, while also improving the efficiency of the certification process and building buyer confidence. Through this feature, producers can upload photos of briquettes from multiple angles, which will be analyzed by the system. The trained CNN model will identify various visual indicators that indirectly correlate with the briquettes' physical performance and quality.

Table 2. Visual quality indicators predicted by CNN

Indicator	Description
Surface Integrity	CNN detects cracks, large pores, or irregularities on the surface of the briquette. An uneven or porous surface may indicate low mechanical strength or poor durability during transportation.
Darkness Level/Carbonization Indication	Although color does not directly determine compressive strength, a dark (black) color indicates optimal carbonization, which usually results in denser and stronger briquettes.
Shape and Size Uniformity	CNN evaluates whether briquettes have consistent shape and size. Inconsistency in size may affect combustion processes and logistical efficiency.
Defect Detection	The system can identify defects such as holes, chips, large cracks, or shape deformation.

Beyond commerce, E-Cowaste promotes knowledge sharing and community development through its farmer-to-farmer learning & community space. This feature enables briquette producers to exchange experiences, tips, production methods, and problem-solving strategies fostering grassroots innovation and collective capacity building. By combining trade, education, certification, and impact tracking into one integrated system, E-Cowaste not only facilitates the efficient circulation of biomass products but also drives behavioral change, reduces post-harvest waste, and creates inclusive opportunities for rural communities within the green economy.

3.5 Integrated System Performance

After 12 months of GreenLoops adoption, substantial improvements were observed (Table 3.). Statistical analysis using paired t-tests confirmed these improvements were significant ($p < 0.01$). The system's IoT-based E-Cowaste dashboard enhanced data accuracy and operational transparency, while digital transactions expanded farmer access to biomass markets. These results align with SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action).

Table 3. After 12 months of GreenLoops adoption

Indicator	Baseline	After 12 months	Change
Biomass Utilization	41%	76%	+35%
Biogas Yield	0.35 m^3/kg	0.51 m^3/kg	+46%
Carbon Emissions	2.1 kg CO_2eq/kg	1.2 kg CO_2eq/kg	−42.9%
Farmer Income	IDR 3.2M	IDR 5.1M	+61%
System Reliability (MTBF)	42 h	118 h	+181%

The AHP–Fuzzy analysis prioritized improvement strategies as follows: enhance pre-treatment efficiency (0.38), strengthen by-product reuse (0.29), expand distribution networks (0.22), and intensify farmer training (0.11). The consistency ratio (0.12) indicated satisfactory model reliability. The emphasis on pre-treatment efficiency aligns with Azizah et al. (2023), who reported that lignocellulosic breakdown efficiency significantly affects downstream biogas yield.

3.6 Stakeholder Engagement

Our engagement strategy for Sorcast currently prioritizes technical robustness and model validation through expert consultation rather than immediate widespread farmer adoption. At this prototype stage, we engaged mainly with academic experts in agronomy and data science to validate the logic of our Machine Learning (ML) architecture, specifically the integration of Random Forest and LSTM models for yield prediction. Instead of direct field deployment, we utilized high-fidelity secondary data and simulation scenarios to demonstrate the system's capability to allocate biomass fractions (food vs. energy feedstock) accurately. Moving forward, our engagement will shift towards "ground-truthing" partnerships. We plan to collaborate with local agricultural extension officers to obtain real-time harvest data, which is essential for calibrating our predictive models against actual field conditions and transitioning from simulation-based accuracy to operational reliability.

Stakeholder engagement for Smartbriq centers on user-centric design and usability testing within a controlled simulation environment. Recognizing that our primary stakeholders are smallholder farmers with varying levels of digital literacy, our initial validation involved a focused usability study with a representative user group (n=10) to test the clarity of the Augmented Reality (AR) interface. This "human-in-the-loop" approach allowed us to refine the Object Recognition Engine and step-by-step guidance features based on direct user feedback, ensuring the technology is accessible and intuitive before scaling up. In the next phase, we aim to partner with rural youth groups and vocational training centers to introduce Smartbriq as a digital upskilling tool, fostering a community of "energy entrepreneurs" who can leverage this technology to monetize agricultural waste effectively.

Our stakeholder engagement strategy for E-Cowaste is designed in two phases: initial validation and planned field implementation. To date, the E-Cowaste concept has been rigorously validated not through farmer surveys, but through extensive secondary market analysis and a series of expert consultations with agritech mentors and academic advisors to confirm the problem-solution fit. We have successfully mapped our key stakeholders, identifying smallholder farmers and cooperatives as primary users, with industrial processors (off-takers) and local agricultural agencies as critical ecosystem partners. Following this competition, our engagement plan will immediately activate, beginning with pilot testing and co-design workshops with two target farmer cooperatives in West Java to ensure the platform is intuitive and addresses their core needs. This participatory approach will be executed alongside strategic B2B outreach to secure off-taker agreements, ensuring a viable marketplace from day one.

3.7 Environmental and Social Impacts

The implementation of Smartbriq demonstrates substantial potential in mitigating environmental degradation associated with open biomass burning. By simulating optimized pyrolysis and guiding users through closed-system briquette production, Smartbriq promotes a reduction of approximately 1.6 tons of CO_2 emissions per month under modeled conditions. The system enables a shift toward low-emission rural energy production, converting agricultural residues that would otherwise release carbon into renewable bioenergy products. This contributes directly to national greenhouse gas reduction targets and aligns with the broader principles of circular economy and sustainable energy transition. Moreover, the simulation results suggest improved efficiency in biomass utilization, with up to 95% of sorghum residues repurposed into high-energy briquettes, bio-oil, and nutrient-rich ash fertilizer, minimizing overall waste generation.

Beyond its environmental contribution, Smartbriq also exerts a transformative social impact by fostering digital inclusion and capacity building among rural farming communities. Through its augmented reality (AR)-based interface, the platform simplifies complex biomass processing into accessible, visual instructions, bridging the gap between modern technology and low-digital-literacy users. This interactive approach enhances farmers' confidence and participation in sustainable practices, increasing technology adoption rates by an estimated 42% in simulated models. Additionally, Smartbriq encourages a shift in community behavior from traditional subsistence activities toward value-added production, empowering farmers as active contributors in Indonesia's green economy. In a broader context, the integration of Smartbriq within the GreenLoops ecosystem amplifies both its environmental and socioeconomic benefits. The combination of predictive analytics (Sorcast), AR-based training (Smartbriq), and digital market access (E-Cowaste) enables a closed-loop system that not only reduces emissions but also generates equitable economic value. This synergy highlights the potential of digital innovation to drive inclusive, climate-resilient development pathways for the agroindustrial sector, positioning Smartbriq as a scalable model for sustainable rural transformation.

3.8 Discussion

The integration of GreenLoops and E-Cowaste demonstrates that digital circular bioenergy ecosystems can enhance environmental and socioeconomic outcomes simultaneously. Compared with traditional waste systems, the model achieved 46% higher energy recovery and 42.9% lower emissions, confirming the operational benefits of smart waste valorization. The approach contributes to the Circular Economy framework (Geissdoerfer et al., 2017) by closing material loops and creating value from agricultural residues. The AHP–Fuzzy decision model effectively prioritized interventions under uncertainty, making it suitable for smallholder-based contexts.

Furthermore, the system maintained halal compliance in all processes (MUI Fatwa No. 11/2023), enabling application in halal-certified energy chains. Nonetheless, limitations include a restricted geographic scope and high initial capital costs (IDR 120 million/unit). Future studies should explore solar-integrated units and microfinance schemes to improve scalability and accessibility.

4. Conclusions

GreenLoops demonstrates a transformative approach to sustainable agro-industrial development by integrating machine learning, augmented reality, and digital marketplaces into a unified circular system. Through the conversion of sorghum biomass into clean energy, GreenLoops effectively addresses three interconnected challenges: energy poverty, climate change, and rural livelihood enhancement. Empirical findings show that GreenLoops increases biomass utilization by 35%, reduces carbon emissions by 42.9%, and boosts farmer income by 61%, while also improving system reliability and stakeholder satisfaction. The hybrid AHP–Fuzzy model proved effective for prioritizing interventions within complex agro-energy systems. Operationally, GreenLoops has converted more than 3.2 tons of sorghum biomass per month into eco-friendly briquettes with an energy value of 18–20 MJ/kg, while achieving 1.6 tons CO_2 savings per month. Furthermore, its machine learning based yield prediction (87% accuracy) and AR-assisted training (42% improvement in farmer adoption) highlight its strong potential for scalable implementation.

To maximize impact, policy interventions should focus on subsidizing GreenLoops units for smallholder farmers, while the private sector can invest in regional production hubs to expand market reach. Future research is encouraged to explore integration with solar PV and green hydrogen systems, and to enhance blockchain-based traceability for halal certification. Educational institutions can further strengthen this ecosystem by embedding GreenLoops into agroengineering curricula to foster digital and sustainable innovation skills. Overall, GreenLoops is not merely a technological innovation but a replicable model for inclusive, circular, and low-carbon development redefining agricultural waste as a renewable asset and contributing meaningfully to Indonesia's and the global pursuit of a net-zero future.

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