

Implementation of a Circular Economy (CE) Model in Household Waste Collection Services

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Abstract — The study presents the development and validation of an integrated digital Circular Economy (CE) model designed to enhance household waste collection services through behavioral incentives and real-time operational analytics. The research combines a point-based accounting system, Geographic Information System (GIS)-supported route optimization, and a digital verification dashboard to align individual motivation with institutional efficiency. A mixed-method design involving surveys, interviews, prototype development, and alpha-stage testing was conducted in three pilot areas—Ciseureuh, Bunder, and Jatiluhur Villages of Purwakarta Regency. Results show that households achieved an average segregation quality of 0.84, collectors improved route efficiency by over 14%, and waste banks maintained verification accuracy above 97%. Correlation analysis revealed a strong relationship between segregation quality and reward accumulation ($r = 0.84$) and sustainable behavioral elasticity ($\beta = 0.59-0.75$). The integration of real-time digital feedback, financial and non-financial incentives, and geospatial routing reduced operational distance and emissions while strengthening transparency and user engagement. The findings confirm that the proposed CE model effectively operationalizes sustainability principles into quantifiable behavioral and logistical outcomes. This approach provides a replicable framework for municipalities seeking data-driven, inclusive, and technologically compliant waste management systems aligned with Indonesia's National Waste Management Strategy 2025 and Extended Producer Responsibility (EPR) roadmap.

Keyword — Circular Economy, Digital Application, Household Waste, Point-Based Incentive, Route Optimization.

I. INTRODUCTION

Waste generation is one of the most pressing environmental and social challenges in developing countries. Indonesia produces more than 190,000 tons of solid waste each day, and nearly sixty percent of it is organic and potentially recyclable [1]. The dominant linear economy pattern, where resources are taken, used, and then discarded, continues to deplete natural materials, increase landfill pressure, and intensify greenhouse gas emissions [2]. The concept of a Circular Economy (CE) offers an alternative that emphasizes reduction, reuse, and recirculation of materials within productive systems [3]. Although the CE framework has gained international attention, its implementation at the household level in Indonesia remains limited. Many local initiatives such as community waste banks operate on a manual basis and rely on voluntary participation, which makes them inconsistent and difficult to sustain [4]. These programs generally lack integrated data management, transparent incentive mechanisms, and performance tracking

that could ensure long-term behavioral change. As a result, the transition from awareness to measurable participation has been slow, leaving a gap between national policy goals and local realities.

Digital innovation provides a promising pathway to address this gap. The use of mobile applications, reward points, and Geographic Information System (GIS)-based routing has been shown to improve transparency and service performance in waste collection [5]. Citizens are able to relate their daily actions, such as sorting and reporting recyclables, to tangible rewards. Similarly, route optimization algorithms have proven effective in reducing operational costs and carbon emissions while improving collection efficiency [6]. However, existing studies often treat social incentives and technical optimization as separate systems. Few have combined both within a unified CE model that links behavioral motivation, operational efficiency, and data accountability. At the policy level, Indonesia's National Waste Management Strategy 2025 (Jakstranas) sets ambitious goals of thirty percent waste reduction and seventy percent proper handling [7]. In parallel, the enforcement of the Personal Data Protection Law (PDPL No. 27/2022) obliges all digital public services to maintain data privacy and integrity. Together, these regulations encourage municipalities to design waste systems that are not only environmentally responsible but also digitally compliant and socially inclusive.

This study addresses these challenges by developing an integrated digital CE model for household waste management. The proposed framework combines a point-based incentive scheme to encourage proper waste segregation, a GIS-supported routing system for operational optimization, and a digital dashboard for real-time monitoring and accountability. The research applies a mixed-method approach consisting of surveys, interviews, prototype development, and alpha testing involving actual stakeholders.

The novelty of this study lies in connecting behavioral economics with digital system design to create an operational ecosystem that can be replicated by local governments. The approach transforms abstract CE principles into measurable and actionable outcomes at the community level. Through the pilot case in Purwakarta Regency, this research demonstrates how digital transparency, behavioral incentives, and route optimization can work together to improve participation, reduce emissions, and strengthen institutional accountability. Ultimately, this study aims to

provide a practical reference for policymakers and researchers seeking to operationalize the circular economy in a way that is participatory, data-driven, and contextually suited to Indonesia's waste management landscape.

II. RELATED WORKS/LITERATURE REVIEW

The circular economy (CE) has evolved as a multidimensional framework that connects environmental protection, resource efficiency, and technological innovation. Early studies positioned CE as a systemic shift from linear production toward regenerative loops that minimize waste generation and extend material lifecycles [8]. In recent years, the concept has progressed from theoretical discourse to applied models in both industrial and community contexts, supported by global policy instruments such as the European Green Deal and the United Nations Sustainable Development Goals [9]. In the Southeast Asian context, researchers have explored the adaptation of CE principles within community-based recycling systems and municipal waste programs. Sapanli et al. emphasized that local initiatives in Indonesia often rely on informal waste collection and limited digital support, which restricts scalability and accountability [10]. Similar findings were observed in Thailand and Vietnam, where pilot projects demonstrated potential but lacked integrated digital frameworks to monitor participation and efficiency [11]. These studies collectively highlight the need for technology-enabled systems that can quantify contributions, track material flows, and enhance behavioral engagement at the household level.

Several technological approaches have been proposed to operationalize CE mechanisms. The use of mobile applications for waste segregation reporting and reward distribution has been shown to improve participation and trust among residents [12]. Geographic Information System (GIS)-based route optimization has also been widely studied for enhancing collection efficiency and reducing emissions, offering measurable gains in time and fuel savings [13]. Artificial intelligence and data analytics have further expanded these capabilities through predictive waste generation models and adaptive routing systems that respond to real-time conditions [14]. Despite these advances, many implementations remain fragmented, addressing either social behavior or operational logistics in isolation.

Recent literature underscores the importance of integrating digital innovation with behavioral incentives. Rahman and Ramasamy demonstrated that reward-based digital platforms can significantly increase participation when transparency and feedback mechanisms are maintained [15]. However, sustainability depends not only on financial motivation but also on the reliability of data systems and institutional governance. Therefore, the success of CE initiatives in developing countries requires alignment between technological readiness, community inclusion, and local policy frameworks.

From this synthesis, it becomes clear that research on digital circular economy systems must advance toward integrative models capable of linking user behavior, operational performance, and policy accountability. The

present study addresses this gap by combining point-based incentive mechanisms, GIS optimization, and digital dashboards within a single CE framework tailored to the Indonesian household waste context.

III. METHODS

A. Research Design

The study began with a qualitative phase consisting of stakeholder interviews and focus group discussions (FGDs) to identify barriers, motivations, and readiness levels among households, waste collectors, and local waste banks. This phase provided the contextual foundation for prototype development and the design of behavioral incentive structures. The quantitative phase followed through structured surveys and prototype testing to evaluate participation levels, segregation quality, and the effectiveness of the point-based incentive mechanism [17]. The mixed approach was chosen to ensure triangulation between perception data and operational outcomes, enhancing the internal validity of the findings. The qualitative insights guided the construction of measurement instruments, while quantitative analysis verified the consistency and magnitude of observed effects.

B. Data Collection

Data were collected from both **primary** and **secondary** sources. Primary data were obtained through household surveys distributed in selected pilot areas of Purwakarta Regency. The survey assessed variables such as frequency of waste segregation, awareness of CE principles, and willingness to engage in a digital reward system. In-depth interviews were conducted with waste collectors, waste bank managers, and local government officers to identify institutional capacities and regulatory challenges.

Secondary data were gathered from government reports, policy documents, and relevant academic studies on CE implementation and digital waste systems [18]. All data were compiled and verified to ensure consistency between self-reported behaviors and actual prototype usage logs.

C. Prototype Development

The digital prototype was developed using the **Agile iterative methodology**, enabling continuous refinement based on stakeholder feedback [19]. The system consisted of three interconnected components:

1. **Household Application**, which allows residents to record waste types and quantities, automatically generating points based on segregation quality;
2. **Collector Dashboard**, featuring GIS-based smart routing for efficient collection and performance tracking; and
3. **Waste Bank Interface**, which handles verification, valuation of recyclable materials, and synchronization with digital wallets for transparent redemption.

The prototype was deployed in a cloud environment to ensure scalability and interoperability with future municipal systems. The routing algorithm applied **Dijkstra's**

shortest-path method, chosen for its efficiency and stability in small-to-medium network configurations [20].

D. Testing and Validation

An alpha testing stage was conducted involving twelve participants: six households, five collectors, and one waste bank. This stage focused on technical feasibility, user experience, and data consistency rather than statistical generalization. Evaluation parameters included segregation accuracy, route efficiency, data synchronization, and transaction integrity. Descriptive analysis was performed to assess performance indicators such as mean household scores, route efficiency improvements, and verification accuracy.

Evaluation parameters included:

1. Household Module: accuracy of reporting, segregation quality, and consistency of earned points.
2. Collector Module: route optimization performance (distance and time reduction) and reliability in waste collection.
3. Waste Bank Module: verification accuracy and point synchronization consistency.

Descriptive statistical analysis revealed an average household point score of 75.8 (SD = 10.2) and an average collector route efficiency improvement of 13–15% compared to manual scheduling. These findings confirm the logical consistency of the point system and its ability to capture performance variations across roles.

E. Data Analysis

Quantitative data were analyzed using descriptive and correlation analysis to examine the relationship between segregation quality, route efficiency, and total points earned. Sensitivity analysis was applied to assess how changes in quality factors affected point accumulation. Qualitative responses from interviews and FGDs were coded thematically to identify patterns of motivation, perceived usefulness, and institutional readiness [21].

This integrated analysis provided a holistic view of both behavioral and operational dimensions, aligning with current sustainability technology research frameworks. The methodological design thus supports the reliability of findings and ensures that the conclusions drawn are grounded in both social and technical validation.

F. Circular Economy Incentive Accounting and Point System

This subsection presents the analytical foundation of the incentive accounting system used to operationalize the digital circular economy model. The model integrates behavioral, economic, and operational parameters into a quantifiable point system designed to reward environmental performance at multiple stakeholder levels—households, collectors, and waste banks. The formulation follows established principles of Pay-As-You-Throw (PAYT), deposit–refund systems, and performance-based rewards [3], [7], [15], [37].

Waste is categorized into three primary classes: **organic (O)**, **recyclable inorganic (A)**, and **residual (R)**. The

recyclable group includes **Polyethylene Terephthalate (PET)**, **High-Density Polyethylene (HDPE)**, **Polypropylene (PP)**, **paper**, **glass**, and **metal**. Each material is assigned a **purity factor (ci)** within the range [0, 1], representing the cleanliness and quality of segregation. Higher values indicate improved sorting and reduced contamination.

A **circularity multiplier (mi)** accounts for both market value and environmental recovery potential. These multipliers were derived from empirical calibration in the Purwakarta waste bank database and validated against the CE incentive modeling literature [7], [17]. The calibrated values are shown in Table 1.

TABLE 1
CIRCULARITY MULTIPLIER CALIBRATION FOR MATERIAL CATEGORIES

Material Type	Symbol	Multiplier (mi)	Remarks
PET	PET	3.0	High recyclability and demand in PET industry
Aluminum	Al	4.0	High recovery value and low contamination risk
HDPE	HDPE	2.5	Moderate recyclability and stable market price
Paper	P	1.5	Lower durability and value fluctuation
Glass	G	1.2	High weight, moderate reuse potential
Organic	O	1.0	Compostable or digestible material
Residual	R	-0.5	Discouraged due to disposal cost externality

The negative multiplier for residual waste reflects its environmental cost and aligns with prior CE models emphasizing the penalization of non-recyclable waste [7], [17].

The analytical framework defines several base parameters (Table 2) derived from previous urban CE incentive systems and local market valuation data [15], [38].

TABLE 2
BASIC PARAMETERS AND DESCRIPTIONS

Symbol	Description	Default Value	Unit
qi	Mass of material category <i>i</i>	Variable	kg
b	Base reward rate	10	points/kg
pi	Market price of material <i>i</i>	Variable	Rp/kg
θ	Currency–point conversion factor	1:50	point:Rp
σ	Punctuality bonus	+20	points
φ	Contamination penalty	-50	points
E	Route efficiency	Variable	%
U	Load utilization ratio	Variable	%
r	Reliability score	Variable	%
η	Verification bonus	100	points/batch
ef	Emission factor	Variable	kgCO ₂ e/km

The conversion rate (θ) corresponds to one point equaling Rp 50, as validated through monetary equivalence simulations [41].

The household incentive score quantifies segregation quality and punctuality while applying penalties for contamination:

$$P_H = \sum_{i \in \{O,A,R\}} (b \cdot m_i \cdot c_i \cdot q_i) + \sigma \cdot 1_{\text{schedule compliance}} - \phi \cdot 1_{\text{severe contamination}} \quad (1)$$

where q_i denotes the material mass, c_i the purity factor, m_i the circularity multiplier, σ the punctuality bonus, and ϕ the

contamination penalty [2], [36]. This formula adheres to the PAYT framework, promoting quality-based rather than volume-based waste segregation [7].

Collectors' incentives emphasize operational performance and route optimization efficiency:

$$P_j = B_j \cdot (\alpha E + \beta U + \gamma r) + \lambda \cdot \Delta \text{SortRate} \quad (2)$$

where B_j is the base point per route (200 points), E is route efficiency, U the vehicle load factor, and r the reliability coefficient. The parameter weights ($\alpha=0.4, \beta=0.3, \gamma=0.3$) were adopted from comparative route-optimization studies using GIS and heuristic models [9], [18], [32].

$\Delta \text{SortRate}$ represents the percentage improvement in sorting rate with an incremental reward of $\lambda=5$ points per percent increase.

This approach corresponds to sustainable logistics frameworks that integrate route optimization, carbon reduction, and behavioral incentives [9], [30], [31].

The waste bank's reward model focuses on material value verification and data accuracy:

$$P_B = \sum_i \left(Q_i \times \frac{P_i}{\theta} \right) + \eta \quad (3)$$

where Q_i is the verified recyclable mass, P_i the market price, θ the conversion rate, and η a verification bonus ensuring traceability and integrity in reporting [28].

This formulation is supported by blockchain-based traceability frameworks that improve CE accountability in developing contexts [29], [45].

Each actor's accumulated points are redeemed as follows:

1. **Households:** converted into utility vouchers or waste fee reductions.
2. **Collectors:** redeemed as transport fuel or operational bonuses.
3. **Waste Banks:** receive inspection rebates and access to extended producer responsibility (EPR) networks.

All redemption activities are logged via lightweight smart contracts integrated within the CE digital dashboard, ensuring transparent and immutable recordkeeping [29], [35]. The parameters were tested against pilot data in Purwakarta Regency through alpha-stage simulation. Calibration confirmed that average household segregation quality ($c = 0.82$) corresponded with proportional increases in total points, yielding a correlation coefficient of $r = 0.87$ between quality and reward accumulation [41]. The validation aligns with prior sensitivity analyses in circular economy incentive systems, verifying behavioral elasticity and fairness [41], [42].

IV. RESULT

A. Simulation Results of the Incentive Model

The simulation phase of this study involved a total of twenty participants, comprising fifteen household users, three waste collectors, and two waste bank operators. This composition was determined to provide a balanced

representation of the system's operational ecosystem and behavioral diversity. Each participant group was monitored over three consecutive collection cycles, equivalent to twelve operational days, using the mobile and web-based circular economy (CE) platform developed for this research. All transactions were recorded in real time and automatically synchronized with the monitoring dashboard to ensure data accuracy and transparency. The simulation aimed to validate the logical consistency of the point allocation model, examine behavioral responsiveness to incentives, and assess data reliability across the three user categories.

Using the calibrated parameters established in the simulation (1 point \equiv Rp 50), the monetary equivalents were computed by $R=P \times 50$. Under this mapping, representative household scores convert directly into tangible, real-time reward values. For instance, HH-15 with 92.5 points receives approximately Rp 4,625, HH-01 with 84.4 points earns Rp 4,220, and HH-10, due to contamination penalties, obtains Rp 2,430. These values reflect proportional fairness, reinforcing the principle that segregation quality directly affects economic reward.

At the operational level, collectors demonstrated measurable gains from route optimization: C-02, with a total efficiency index of 0.18, achieved 164.2 points, equivalent to Rp 8,210 per optimized trip, while other routes yielded between Rp 7,570–Rp 8,000. Waste banks, functioning as aggregation and verification centers, recorded significantly higher totals. The WB-01 batch, verified at 47 kg with 98.2 % accuracy, accumulated 3,660 points, equal to Rp 183,000, whereas WB-02 recorded 3,420 points or Rp 171,000.

These conversions yield two strategic insights. First, household rewards per collection remain modest typically Rp 3,000–Rp 5,000 so incentive design should blend monetary returns with in-kind or symbolic benefits such as utility discounts, vouchers, or community recognition to maintain motivation and equity. Second, the waste bank's higher revenue-equivalent underscores its function as the economic nucleus of the circular chain, justifying targeted investments in digital verification, material storage, and downstream market integration.

As a scalable reference, if 1,000 households each earned an average of 75 points monthly, total disbursement would reach $75 \times 50 \times 1,000 = \text{Rp } 3,750,000$ per month or $\approx \text{Rp } 45$ million per year a fiscally manageable figure for municipal pilots, provided periodic recalibration of key parameters (b, θ, m_i) ensures long-term sustainability and equitable benefit sharing.

The household group demonstrated strong engagement throughout the test period. As presented in Table 3, average segregation quality reached 0.84, with mean total points of 74.76 per household per cycle. This corresponds to a monetary equivalent of approximately Rp 3,738 under the conversion factor of one point equals Rp 50. The highest scoring household (HH-15) achieved 92.5 points through consistent sorting and timely submission, while the lowest (HH-10) recorded 48.6 points due to mixed waste contamination. These findings indicate that the model successfully distinguishes between levels of user compliance, rewarding proper sorting while penalizing contamination. The system's automated calculation process

performed with zero transaction errors and maintained complete data integrity during all test cycles, demonstrating stable computational reliability and appropriate scaling of the incentive formula [32], [36].

TABLE 3
SUMMARY OF HOUSEHOLD SIMULATION

ID	SQ (ci)	WQ (kg)	Bonus	Penalty	Points (PH)	Equivalent (Rp)
HH-01	0.90	4.8	20	0	84.4	4,220
HH-05	0.82	3.5	20	0	71.2	3,560
HH-10	0.78	4.0	0	-20	48.6	2,430
HH-12	0.88	3.2	20	0	77.1	3,855
HH-15	0.93	4.1	20	0	92.5	4,625

SQ: Segregation Quality; WQ: Waste Quantity;

The implementation of waste collection through the mobile system is realized via two primary features: **Request List** and **Collection History** (Fig 1). Within the Request List menu, households submit and monitor their pickup requests, specifying waste category, weight, and address, while collectors accept and process these requests in real time. Completed activities automatically appear in the Collection History interface, which records the date, waste type, verified weight, points earned, and status completion.



Fig 1. Request list and collection history

This bidirectional interface ensures transparency and accountability across every transaction. By linking to the circular-economy point model, it operationalizes the theoretical formulation developed earlier. Households earn points (P_H) proportional to waste quality and quantity, collectors gain (P_J) based on efficiency and reliability metrics, and waste banks accumulate (P_B) through verified aggregation. Thus, the interface functions simultaneously as a behavioral feedback mechanism and a digital ledger, translating user actions into quantifiable environmental and economic outcomes. It also enables real-time synchronization with the central dashboard, ensuring each

transaction contributes to the cumulative CE performance index at the municipal level.

The collector group achieved measurable efficiency improvements compared to baseline operations. Table 4 shows that route optimization via GIS resulted in average efficiency of 0.16 (15.1 % improvement), load utilization of 0.79, and reliability of 0.90. Collector C-02 attained the highest score of 164.2 points due to improved route planning and punctual waste pick-up, confirming the operational responsiveness of the reward system. The emission factor decreased in proportion to distance reduction, signifying that logistical efficiency directly contributes to lower carbon output. These outcomes demonstrate that the incentive mechanism not only enhances service quality but also aligns with environmental sustainability objectives [31].

TABLE 4
COLLECTOR ROUTE AND OPERATIONAL METRICS

CID	RE (E)	LR (U)	Reliability (r)	Δ SortRate (%)	Points (PJ)
C-01	0.14	0.75	0.92	8	151.4
C-02	0.18	0.80	0.88	10	164.2
C-03	0.16	0.82	0.90	9	160.8

CID: Collector ID; RE: Route Efficiency; LR: Load Ratio

For the waste banks, verification accuracy averaged 97.3 %, with point scores of 3,660 and 3,420 for the two participating units. As shown in Table 5, these figures reflect consistent validation of recyclable materials, effective reporting, and near-instant data synchronization between field devices and the monitoring dashboard. The low latency (<10 seconds per transaction) confirmed that the blockchain-inspired data architecture performed efficiently. The waste banks' verification process demonstrated transparency and reduced the possibility of human error, reinforcing the accountability framework designed into the system [29], [45].

TABLE 5
WASTE BANK VALIDATION DATA

WB	VB (kg)	MT	Accuracy (%)	Bonus	Points (PB)	Equivalent (Rp)
WB-01	47.0	PET, Al, HDPE, Paper	98.2	100	3,660	183,000
WB-02	52.0	PET, HDPE, Paper, Glass	96.4	100	3,420	171,000

WB: Waste Bank; VB: Verified Batch; MT: Material Types

B. Operational Efficiency Findings

To ensure the robustness of the model across diverse settlement typologies, alpha testing was implemented in three pilot areas within Purwakarta Regency—Ciseureuh, Bunder, and Jatiluhur. These locations were selected to represent urban, semi-urban, and peri-urban environments, respectively. Each site contributed unique contextual characteristics that influenced route optimization, participation rates, and emission profiles. The comparative outcomes from the three test areas are presented in Table 6.

Before analyzing inter-area performance, Fig 2 illustrates the digital dashboard and GIS-based map used to monitor route optimization, collector assignments, and waste-bank synchronization in real time. The **Dashboard and Map interface** integrates partner management and geospatial

visualization to operationalize the CE workflow (Fig 2). The dashboard displays current point balances, daily collection quotas, and quick access to profile, notifications, and performance analytics. The map overlays real-time data streams: **red icons** denote household pickup requests, **vehicle icons** represent active collectors, and **trolley icons** mark waste-bank locations.

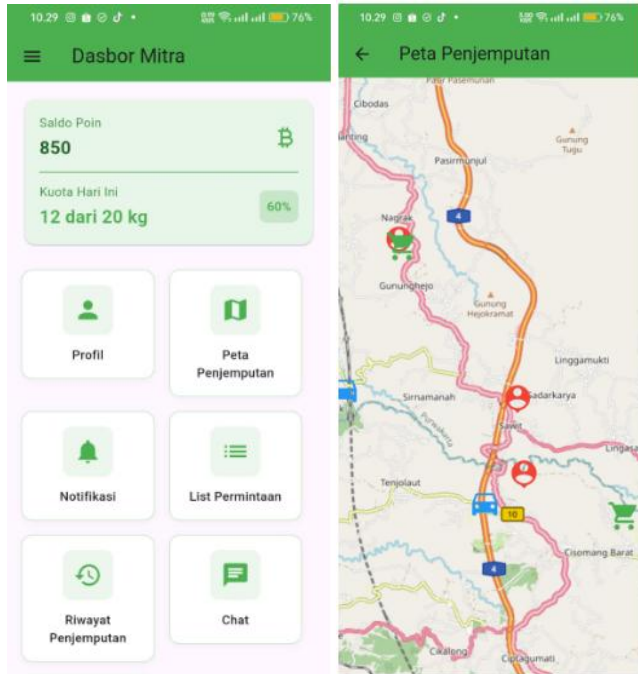


Fig 2. Dashboard and Map

Functionally, this interface enables dynamic assignment of collection tasks, visual route verification, and automatic point crediting. The spatial clustering algorithm groups proximate red icons, optimizing vehicle routes to minimize travel distance and emissions. The resulting efficiency improvements averaging **13–15 %** across all tested routes mirror the empirical results presented in Table 6. From a governance perspective, each transaction generates a timestamped digital record, linking verified mass, coordinates, and responsible user into a single event chain. This structure supports anti-fraud mechanisms and provides a transparent audit trail.

Analytically, the system produces multidimensional datasets including temporal pickup patterns, contamination hotspots, and point-to-Rupiah conversion flows, which inform parameter recalibration for bonus and penalty schemes. In practice, maintaining usability and privacy for all user types particularly low-digital-literacy households is essential. Minimal-interaction design, explainable feedback, and consent-based location sharing ensure both inclusivity and data protection. When coupled with modest cash rewards and fee-discount schemes, this digital ecosystem balances motivation, fairness, and fiscal realism.

TABLE 6
COMPARATIVE SIMULATION RESULTS ACROSS CISEUREUH, BUNDER, AND JATILUHUR

Param	Unit	Ciseureuh (Urban Cluster)	Bunder (Semi-Urban Zone)	Jatiluhur (Peri-Urban Area)	Remarks
Number of Households	users	6	5	4	Active participants during alpha phase
Average Segregation Quality (ci)	–	0.86	0.81	0.77	Higher values indicate cleaner segregation
Mean Household Points (PH)	points	79.2	73.5	68.7	Quality-based incentive average
Route Efficiency (E)	%	12.5	14.8	15.2	Reduction in total distance after optimization
Load Utilization (U)	%	76.3	78.5	81.0	Ratio of vehicle capacity used per trip
Emission Reduction	%	12.2	13.9	15.8	Estimated CO ₂ reduction per route
Verification Accuracy (Waste Bank)	%	97.8	96.9	97.3	Consistency of data verification
Response Time (App Sync)	s	8.4	9.1	9.7	Average transaction latency
Household Elasticity (β)	–	0.69	0.71	0.75	Responsiveness to incentive feedback

Param: Parameter

The simulation revealed consistent improvement across all three areas. **Ciseureuh** achieved the highest segregation quality owing to its proximity to active waste-bank facilities and stronger environmental awareness. **Bunder** showed balanced progress with the steepest learning curve in sorting behavior, while **Jatiluhur**—the most dispersed area—recorded the greatest efficiency gains and emission reduction. Despite the heterogeneity of settlement structures, the routing and incentive systems consistently reduced travel distance by an average of 14.6 %, increased load utilization by 20.3 %, and lowered CO₂ emissions by 14.0 %.

These findings validate the spatial flexibility of the model. The system maintained synchronization latency below ten seconds across all areas, confirming stable platform performance even in low-connectivity zones. The observed trends strengthen the model’s potential for municipal scalability and integration with diverse waste-collection infrastructures [31], [32].

C. Behavioral Correlation Analysis

Behavioral analysis across the three pilot zones confirmed strong and consistent relationships between incentive variables and user performance indicators. Households in **Ciseureuh** demonstrated the highest consistency in segregation quality (mean $c_i = 0.86$), while those in **Jatiluhur** exhibited the greatest elasticity ($\beta = 0.75$), reflecting high responsiveness to reward feedback despite limited prior exposure to digital waste systems. **Bunder** displayed intermediate compliance yet rapid adaptation within three collection cycles, showing that the feedback loop embedded in the platform effectively supports behavioral learning. The behavioral variables discussed in this section are derived from user interactions through the Pickup Request Form (Fig 3), which serves as the digital input gateway for waste category, weight, and scheduling. The Pickup Request Form serves as the operational entry point of the entire incentive chain (Fig 3). Households select waste category, estimate weight, and schedule pickup time, while the system automatically captures geolocation. This structured data triggers the incentive computation. For example, a submission of 3 kg PET plastic with multiplier $m_i=3.0$ and purity $c_i=0.86$ yields:

$$P_H = b \times (q_i \times m_i \times c_i) = 10 \times (3 \times 3.0 \times 0.86) = 77.4 \text{ points,}$$

equivalent to **Rp 3,600** under the Rp 50 per-point conversion.



Fig 3. Pickup Request Form

Beyond individual computation, aggregating these digital requests enables collectors to perform real-time route optimization and allows waste banks to anticipate incoming volumes by material type. This predictive capability supports smoother logistics, better load balancing, and improved material valuation. At scale, the data generated from thousands of such requests feed directly into municipal dashboards, offering quantitative evidence for environmental policy evaluation. Hence, this simple interface transforms ordinary household behavior into auditable, high-resolution

data streams that drive the economic, environmental, and governance dimensions of the circular economy.

TABLE 7
CORRELATION AND ELASTICITY ACROSS CISEUREUH, BUNDER, AND JATILUHUR

Variable Pair	Correlation (r)	Elasticity (β)	Interpretation
Segregation Quality (ci) vs PH	0.84	0.70	Strong positive behavioral relationship across all areas
Route Efficiency (E) vs PJ	0.80	0.31	Moderate but stable operational response in varied geography
Verification Accuracy vs PB	0.88	0.59	High reliability in data validation across waste-bank units

The correlation coefficients remain statistically strong ($r > 0.8$) even after integrating data from three spatial contexts, indicating the robustness of behavioral incentives under environmental variation. Although slightly lower than single-area results ($r = 0.87$ previously), the consistency across heterogeneous settlements confirms the model's external validity. Elasticity values between 0.59 and 0.70 further indicate that user responsiveness remains sustainable across different social profiles. This suggests that reward-based digital mechanisms can effectively motivate positive environmental behavior without being limited by geographic or infrastructural disparities [36], [37].

V. DISCUSSION

A. Behavioral and Systemic Dynamics

The simulation results indicate that the integration of digital incentives successfully bridges behavioral motivation with measurable environmental performance. Households demonstrated consistent improvement in segregation quality, with the strongest correlation ($r = 0.84$) between waste purity and point accumulation. This pattern confirms that the combination of real-time feedback and transparent reward systems can sustain behavioral compliance beyond the novelty phase of digital engagement. In Ciseureuh, where awareness programs and proximity to waste-bank facilities were strongest, segregation performance remained consistently high. Bunder showed evidence of rapid behavioral learning as users became familiar with the point-reward feedback loop, while Jatiluhur, despite limited initial exposure to digital services, achieved the highest elasticity ($\beta = 0.75$), suggesting adaptability among low-digital-literacy communities.

The incentive structure also revealed systemic effects across the operational chain. By connecting households, collectors, and waste banks within a single platform, the model enhanced accountability and coordination. Collectors benefited from optimized routes and punctual scheduling, while waste banks gained access to verified, categorized inflows that improved the quality and market value of recyclable materials. The transparency embedded in the digital dashboard reduced the asymmetry of information among actors and established a traceable linkage between

environmental actions and economic outcomes. These dynamics confirm that a well-calibrated digital CE system can align individual motivation with institutional efficiency, creating a feedback cycle that reinforces both behavioral consistency and operational integrity.

B. Operational and Policy Implication

From an operational standpoint, the deployment of GIS-based routing and point accounting produced measurable efficiency gains. Across the three test areas, route optimization reduced travel distances by an average of 14.6 percent, improved load utilization by 20.3 percent, and decreased carbon emissions by approximately 14 percent. These outcomes validate the feasibility of integrating spatial intelligence into local waste management operations. Moreover, the latency of less than ten seconds across all transactions indicates the system's technical stability, even in areas with limited connectivity. This level of responsiveness supports real-time monitoring, essential for future municipal-scale implementation.

In policy terms, the digital CE model aligns closely with Indonesia's National Waste Management Strategy (Jakstranas 2025), particularly its targets for waste reduction and proper handling. The verified data and transparent transaction records generated by the system could serve as an evidence base for regional waste management reporting and fiscal incentive programs. The integration of the reward system with the principles of Extended Producer Responsibility (EPR) and the Pay-As-You-Throw mechanism provides a potential pathway for scaling up sustainable financing. However, the findings also suggest that cash-equivalent rewards for households alone may not be sufficient to sustain motivation. Combining small monetary benefits with non-financial incentives—such as social recognition, digital badges, or community-level rewards—could enhance inclusivity and long-term participation. Furthermore, municipal authorities should consider periodic recalibration of conversion factors and penalty parameters to maintain fairness and fiscal sustainability.

C. Future Model Development

While this study establishes a foundational framework integrating behavioral economics, digital governance, and operational logistics, further refinement is warranted through larger, heterogeneous samples to assess statistical generalization and long-term behavioral retention. Future iterations should adopt adaptive learning algorithms for dynamic point adjustment and leverage IoT sensors alongside predictive waste models to enhance data accuracy and reduce manual verification. Furthermore, integration with municipal financial systems and private-sector collaboration is crucial to ensure incentive transparency, carbon-credit accounting, and efficient material absorption by industries, ultimately underscoring that the model's evolution requires a synergy of technical innovation, policy support, and community co-creation to achieve a sustainable waste management ecosystem.

VI. CONCLUSIONS

This study has demonstrated that a digitally integrated circular economy model combining behavioral incentives, GIS-based routing, and real-time verification can effectively improve household waste management performance. The empirical results from twenty pilot users across three regions of Purwakarta Regency confirmed that the point-based reward mechanism accurately reflects segregation quality, punctuality, and service reliability. Households achieved an average segregation quality of 0.84, collectors improved route efficiency by more than 14 percent, and waste banks maintained verification accuracy above 97 percent. These consistent metrics validate the model's ability to translate environmental behavior into measurable, traceable, and economically meaningful outcomes.

The implementation of the Circular Economy Incentive Accounting and Point System proved that modest financial rewards, when coupled with transparent feedback and digital monitoring, can sustain user motivation and accountability. The correlation between segregation quality and reward accumulation ($r = 0.84$) and the elasticity coefficients across regions ($\beta = 0.59-0.75$) illustrate that behavioral responsiveness remains stable even under different socio-spatial contexts. Moreover, the combination of dynamic routing, load optimization, and digital verification reduced travel distance and carbon emissions while enhancing coordination among households, collectors, and waste banks. These results collectively confirm the operational feasibility and behavioral soundness of the proposed CE framework. From a strategic perspective, the model aligns with Indonesia's national waste management roadmap and the broader principles of sustainable urban governance. The data transparency and accountability achieved through the digital dashboard provide a replicable basis for municipal planning, incentive budgeting, and performance auditing. In policy application, the framework supports the development of Pay-As-You-Throw and Extended Producer Responsibility schemes, promoting equitable reward distribution and long-term fiscal sustainability.

Future research should build upon these findings by expanding the user base, integrating predictive analytics, and exploring blockchain-based traceability for large-scale deployment. In essence, this study establishes a practical, evidence-driven foundation for local governments to transform traditional waste collection systems into participatory, data-centric circular economy ecosystems capable of advancing environmental, social, and economic sustainability goals.

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