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A Prototype-Driven Approach for e-Waste Redistribution

Heni Rachmawati[1*], Adriza Rafly Azlami[2], Yuli Fitrisia[3], Wenda Novayani[4]
Politeknik Caltex Riau, Pekanbaru, 28265, Indonesia
henni@pcr.ac.id[1*], adriza@graduate.pcr.ac.id[2], uli@pcr.ac.id[3], wenda@pcr.ac.id [4]

**Penulis Koresponden*

ABSTRAK

Meningkatnya limbah elektronik (e-Waste) menimbulkan tantangan lingkungan yang serius karena kurangnya kesadaran masyarakat dan terbatasnya akses ke fasilitas daur ulang yang terstandarisasi. Studi ini mengusulkan model redistribusi e-Waste berbasis komunitas yang terintegrasi dengan prinsip Ekonomi Sirkuler, yang diimplementasikan melalui platform seluler. Untuk memastikan pengelolaan e-Waste yang bertanggung jawab, arsitektur ini memiliki alur redistribusi khusus yang menghubungkan pengguna akhir secara langsung dengan pendaur ulang yang terverifikasi. Lebih lanjut, Layanan Berbasis Lokasi (LBS) diimplementasikan tidak hanya untuk pemetaan, tetapi juga sebagai algoritma pencocokan kedekatan spasial menggunakan rumus Haversine untuk mengoptimalkan logistik. Sistem ini dikembangkan menggunakan metodologi prototipe, yang mencakup identifikasi kebutuhan pengguna yang komprehensif dan dua siklus desain iteratif berdasarkan umpan balik pengguna kualitatif. Evaluasi fungsional melalui pengujian black box memvalidasi tingkat keberhasilan 100% di semua skenario integrasi sistem. Selain itu, pengujian usability yang melibatkan 21 responden yang ditargetkan secara demografis, dievaluasi menggunakan kuesioner yang dikembangkan khusus dan menghasilkan skor kelayakan sebesar 91,5%. Temuan ini menunjukkan tingkat penerimaan pengguna dan efektivitas antarmuka yang tinggi. Pada akhirnya, penelitian ini memberikan kerangka kerja algoritmik untuk pengelolaan limbah elektronik berbasis komunitas, serta membangun solusi digital yang layak untuk redistribusi limbah berkelanjutan.

Kata kunci: *Ekonomi Sirkuler, Kedekatan Spasial , Manajemen Limbah Elektronik, Platform Seluler, Prototipe*

ABSTRACT

The rise of electronic waste (e-Waste) poses a serious environmental challenge due to the public's lack of awareness and limited access to standardized recycling facilities. This study proposes a community-based E-Waste redistribution model integrated with Circular Economy principles, implemented through a mobile platform. To ensure responsible E-Waste management, this architecture features a dedicated redistribution flow connecting end-users directly with verified recyclers. Furthermore, Location-Based Services (LBS) are implemented not merely for mapping, but as a spatial proximity-matching algorithm using the Haversine formula to optimize logistics. The system was developed using a prototyping methodology, encompassing comprehensive user requirement identification and two iterative design cycles based on qualitative user feedback. Functional evaluation via black-box testing validated a 100% success rate across all system integration scenarios. Moreover, usability testing involving 21 demographically targeted respondents, evaluated using a custom-developed questionnaire and yielded a feasibility score of 91.5%. These findings indicate a high level of user acceptability and interface effectiveness. Ultimately, this research contributes an algorithmic and architectural framework for community-driven e-Waste management, establishing a viable digital solution for sustainable waste redistribution.

Keywords: *Circular Economy, Electronic Waste Management, Mobile Platform, Prototype, Spatial Proximity*

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INTRODUCTION

The rapid escalation of electronic waste, or e-waste, has become one of the most urgent sustainability challenges in the digital era. In 2022, global e-waste reached 62 million tons, but only 22.3% was formally collected and properly recycled, resulting in environmental risks and the loss of recoverable materials such as precious metals and rare earth elements [1]. This problem is not only caused by the increasing volume of discarded electronic devices, but also by weaknesses in the redistribution and recovery ecosystem. In many developing regions, e-waste handling is still constrained by fragmented collection channels, limited public awareness, low accessibility to recycling services, and weak coordination between device owners, collectors, refurbishes, and recyclers [2]. As a result, many reusable or repairable electronic products are either stored unused, informally discarded, or disposed of without entering circular economy pathways such as reuse, refurbishment, resale, and component recovery [3].

Previous studies have proposed various digital and optimization-based solutions to improve waste management. However, most existing systems focus on municipal solid waste routing, collection scheduling, or logistics optimization rather than on the behavioral and transactional mechanisms that encourage individual users to participate in e-waste redistribution [4]. Other studies on sustainable waste logistics, including dynamic routing for biowaste and multi-objective models for healthcare waste, contribute to operational efficiency but do not sufficiently address the specific characteristics of consumer-level e-waste exchange, where trust, proximity, device condition, negotiation, and user validation are critical factors [5][6]. Although general Consumer-to-Consumer (C2C) marketplaces enable users to sell used products, they commonly lack e-waste-specific categorization, proximity-based redistribution logic, merchant validation, and mechanisms to distinguish between reusable, repairable, and recyclable electronic items. Conversely, many formal e-waste management systems are government-led or institution-centered, with limited support for direct user interaction, economic incentives, and localized exchange between households and recycling actors. Since incentives, convenience, and perceived trust can significantly influence residents' willingness to participate in recycling platforms [8][9], a critical gap remains between generic marketplace systems and formal e-waste management systems.

To address this gap, this study proposes a mobile-based e-waste redistribution platform that integrates circular economy principles, spatial proximity, and user validation into a single digital ecosystem. The scientific contribution of this study lies not merely in combining common mobile application features, but in designing and evaluating a specialized interaction model for community-level e-waste redistribution. The proposed model connects three main actors: Listers as electronic device owners, Merchants as validated recyclers or refurbishes, and administrators as platform validators. The system incorporates Location-Based Services using the Haversine formula to support proximity-based matching, merchant validation to strengthen platform trust, and transparent negotiation features to facilitate responsible exchange between users. Through this design, the platform aims to bridge the gap between informal second-hand electronic trading and formal circular economy practices.

This study was developed using the Prototype methodology to allow iterative refinement based on user needs and system evaluation. Accordingly, the research questions are: (1) How can a specialized C2C mobile platform be designed to support circular-economy-oriented e-waste redistribution? and (2) How can Location-Based Services facilitate proximity-based matching between Listers and validated Merchants in the e-waste redistribution process? The objectives of this study are to design and develop a responsible e-waste redistribution platform, implement LBS-based discovery and matching between users and merchants, and evaluate how validation and transparent interaction mechanisms can support trust and participation in community-level e-waste management.

METHOD

2.1. Proposed E-waste Management Workflow

The process begins when a Lister uploads the details of an unused electronic item to the mobile platform. The system then applies an LBS-based matching mechanism to identify nearby verified recycling Merchants. The Haversine Formula is used as a standard method to estimate the geographical distance between the Lister and available Merchants. Rather than proposing a new optimization model, this study applies distance-based filtering to support practical proximity matching in community-level e-waste redistribution. After a suitable Merchant is identified, the platform facilitates negotiation and distribution agreement through transparent communication features. Once an agreement is reached, the Merchant collects the item and conducts a triage assessment to evaluate its physical and functional condition. Based on this assessment, the e-waste is classified into three possible conditions:

- **If the item is classified as minor damage**, it proceeds to a repair or refurbish process, allowing the product to re-enter the market and extend its lifecycle.
- **If the item is categorized as damaged**, it undergoes component recovery, where usable parts are extracted for reuse as spare components.
- **If the item is determined to be completely non-functional**, it proceeds to material recycling, where valuable raw materials such as copper, gold, and plastic are extracted.

This structured process ensures optimal resource recovery and supports circular economy principles by maximizing reuse, refurbishment, and material recycling pathways.

2.2. Location-Based Service (LBS) Optimization Model using Haversine Formula

This system applies an LBS-based proximity matching mechanism to support circular-economy-oriented e-waste redistribution. The Haversine Formula is used as a standard geospatial method to calculate the great-circle distance between the Lister and verified recycling Merchants. This study adapts distance-based filtering within a specialized e-waste platform to facilitate practical local matching between users and verified recycling actors. This mathematical formula is selected for its high accuracy in determining the spherical distance between two geographical coordinate points on Earth [10]. The distance (d) is calculated using the following equation:

$$d = 2r\ arcsin(\sqrt{(}sin^2((\varphi_2 - \varphi_1)/2\ cos(\varphi_1)cos(\varphi_2)sin^2((\lambda_2 - \lambda_1)/2))) \quad (1)$$

d = The spatial distance between the Lister and Merchant (in kilometers).
r = The mean radius of the Earth (constant at approximately 6,371 km)
φ_1, φ_2 = The latitude coordinates of the Lister and Merchant (in radians).
λ_1, λ_2 = The longitude coordinates of the Lister and Merchant (in radians).

2.3. Prototyping Methodology

This study employed the Prototype methodology because the proposed e-waste redistribution platform requires continuous alignment between system functionality, user interaction, and circular-economy-oriented service processes. Prototyping enables early visualization and refinement of key workflows [11], including product listing, merchant validation, LBS-based proximity matching, negotiation, and e-waste collection. This method is suitable because the system involves multiple user roles, namely Listers, Merchants, and administrators, each with different interaction needs and validation requirements. Through iterative feedback, the prototyping process helped identify usability issues, improve feature design, and strengthen user trust. Thus, its contribution in this study lies not only in producing a working mobile application, but also in refining a user-centered interaction model for community-level e-waste redistribution. the Prototype methodology was applied through the stages of needs identification, prototype design and evaluation, iterative design refinement, system development using Kotlin and Android Studio, functional and usability testing, and documentation to ensure the system is easy to use. This approach is considered most appropriate to ensure that the developed E-Waste mobile application can effectively answer user needs and minimize the risk of design errors from the initial stage.

Listen to The Customer

The initial prototyping phase identified user requirements in Pekanbaru City through interviews with two key actors, namely the general public as Listers and e-waste collectors as Merchants. Merchant interviews revealed that formal local recycling facilities are almost unavailable, causing most e-waste to be sent to other provinces. As a result, local transactions depend heavily on the assessment of item condition and salvageable components, which justified the need for detailed item descriptions and a dedicated negotiation feature. A questionnaire involving 19 respondents in Pekanbaru further confirmed Lister needs and behavior. The results showed that 73.7% of respondents had sold or recycled used electronics, while 42.1% often found items they wanted to distribute. The main obstacle was the lack of information about nearby recycling service providers (57.9%), which was consistent with the interview findings. Respondents identified location-based search as the most important feature (73.7%), followed by photo upload, offer notifications, and recycling education. Most respondents also considered the application very useful (63.2%). Based on interviews, competitor analysis, and questionnaire results, the main functional requirements were formulated: Merchants need features for searching used electronics by category or location, bidding, price negotiation, and locating the nearest Lister, while Listers need features for uploading item photos and descriptions, finding the nearest Merchant through LBS, and negotiating prices. These requirements are represented in Figure 1 and used as the basis for subsequent system development using the Prototype methodology.

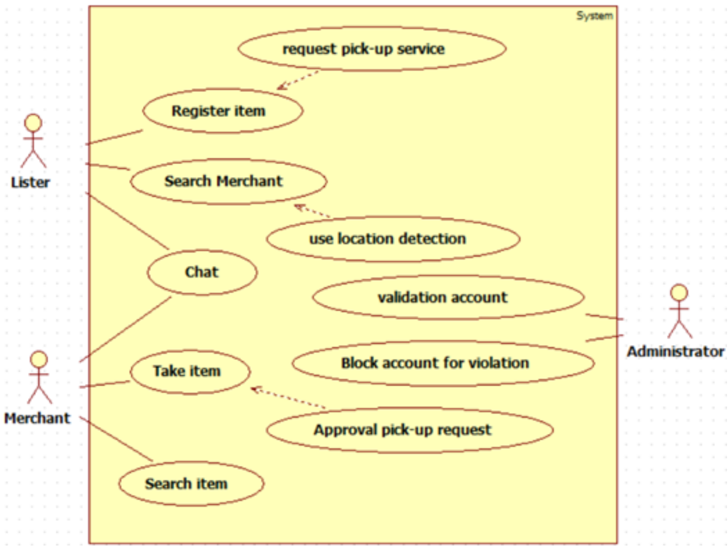

Figure 1. Use-case Diagram

Build and Revise Mock-up

The Build and Revise Mock-Up phase is the core of the Prototype methodology because mock-ups serve as initial models that allow developers and users to evaluate the application design early on. In this study, mock-ups were designed in stages to illustrate the interaction flow and UI/UX appearance of the application, starting from the on-boarding page to the dedicated Admin page. Each mock-up was then tested by potential users to gain an understanding of actual needs in the field. This iterative approach aligns with research findings in [12], which explains that the iterative evaluation process on prototypes allows for early identification of usability issues, allowing for continuous improvement of the design before entering the implementation phase. With this mechanism, every input from Listers and Merchants was used to refine the navigation structure, clarify functions such as location-based search, upload items, and price negotiation by chat, and ensure that the display meets the principles of ease of use. This continuous revision process helps reduce the risk of major design changes in the core development stage and ensures that the resulting mock-ups truly reflect user needs and the context in which the application is used.

Customer Test Drive Mock-up

The platform was developed using a Prototyping approach, starting with requirement identification through preliminary surveys and semi-structured interviews. This phase involved prospective users, namely individuals disposing of electronic waste (Listers) and local e-waste collectors (Merchants), to identify pain points in conventional e-waste disposal and define the platform's core functional requirements. After requirement analysis, the initial design was visualized using wireframes [14], leading to the Customer Test Drive Mock-up stage. This stage enabled early interface and workflow evaluation through direct user feedback, consistent with [13], which emphasizes the importance of early user involvement before complex implementation. Prospective users, including Listers, Merchants, and Admins, evaluated Prototype 1 using direct observation and a think-aloud protocol while performing key tasks such as locating nearby Merchants via LBS, uploading e-waste items, and initiating negotiations. Their feedback revealed usability issues that informed two iterative design cycles to improve accuracy, security, and user experience.

Table 1. Prototype Iteration

Feature /Aspect	Prototype 1	Feedback 1	Prototype 2	Feedback 2
Product Upload (Sell Page)	Location input relied on manual text entry	Users found it difficult to pinpoint the exact pickup location for e-waste	Integrated a Map Picker button to ensure geospatial accuracy	Users confirmed that the Map Picker improved location accuracy
Merchant Trust	Simple registra-tion without strict verifica-tion	Users expressed concern about the legitimacy of recyclers / merchant	Implemented a "Merchant Validation" workflow requiring document upload and Admin approval	Stakeholders agreed that the validation process increased merchant credibility.
Product Discovery	Standard list view only.	Users struggled to identify the nearest recycling partners.	Added a "Nearest Merchant" section on the Home Page.	Users found it easier to identify nearby recycling partners.
Navigati-on	Menu structures were hidden or deep-linked.	Users found it slow to access the "Sell" and "Chat" features.	Adopted a persistent Bottom Navigation Bar	Users confirmed that navigation became faster and easier to access.

Table 1 presents the user feedback and corresponding design modifications across these iterations. The refinements are reflected in the final interface design. For example, the final "Add Product" page (Figure 4a) includes a "Select Exact Location on Map" button to improve location accuracy. Trust concerns were addressed through Merchant Validation (Figure 2), requiring supporting documents for Admin verification. Accessibility and navigation latency were improved by adding a persistent Bottom Navigation Bar on the Main Page (Figure 3), making key features such as "Sell" and "Message" immediately accessible.

3. RESULT AND DISCUSSION

3.1 System Implementation

The results of the application interface design show that all the main elements needed in the e-waste management and distribution process have been accommodated in a systematic display structure. The interface is built to support three types of users, namely Lister, Merchant, and Admin, with the arrangement of pages that reflect the application's operational flow starting from the initial user orientation through the On Boarding page, the authentication process through Login and Registration, to managing transaction activities through the Home, Sell, Offers, Chat, and My Ads pages. In addition, supporting features such as Profile, Edit Profile, Settings, Help, and About Us are designed to strengthen the user experience, while special pages such as Merchant Validation, View Merchant Profile, and the admin panel for verification and report management indicate the existence of a monitoring mechanism and the validity of transactions within the application ecosystem. In the application prototype design, the Merchant validation process is a critical feature to ensure that only authorized and trusted parties can conduct transactions. Validation is performed by filling in registration data and uploading supporting documents, which are then verified by the admin to ensure the accuracy of the information before the Merchant gains full access to the sales features.

In terms of security and interaction, the app implements data encryption to protect personal information and transaction details, system supports two-factor authentication as an additional layer of security. For convenient transactions, the interface is designed with an intuitive UI and includes a chat feature, enabling fast and efficient direct communication between Listers and Merchants. The Lister role can begin the core activities of the application through the item listing features. These activities are supported by the Sell Page, which enables Listers to upload detailed information about electronic waste items, and the My Ads Page, which allows users to manage, monitor, edit, or remove their published listings as shown in Figure 4a.

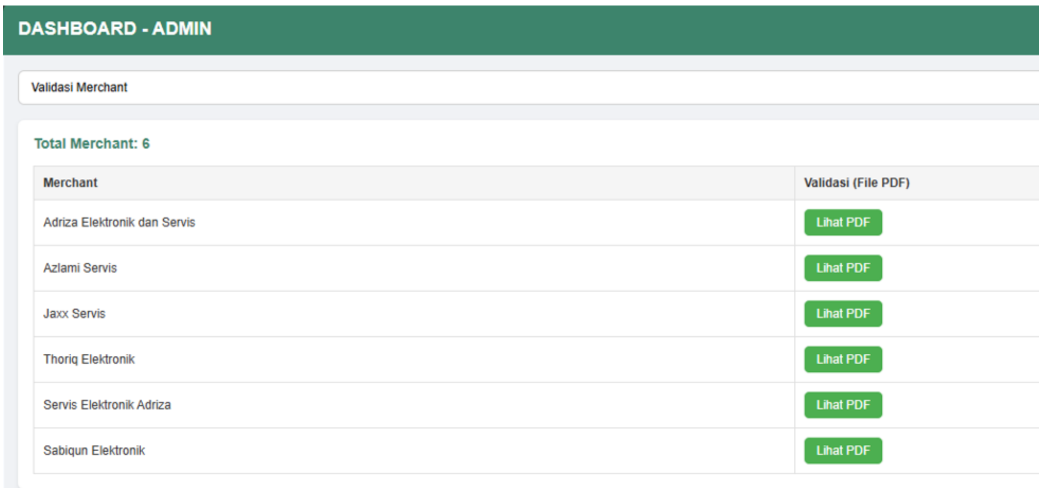

Figure 2. Merchant Validation by Admin Page

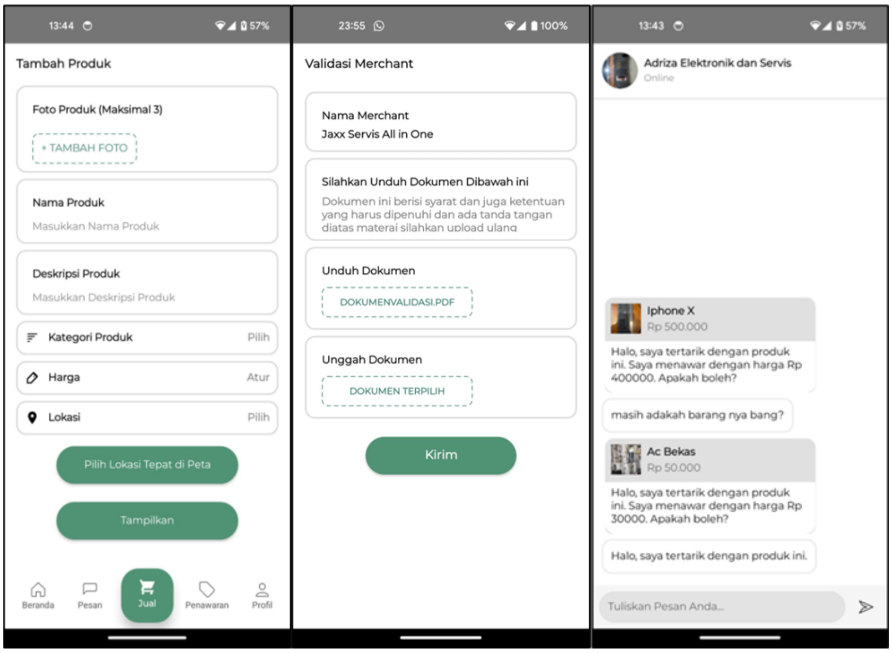

Figure 3. (a) Merchant Registration Page, (b) Validation Documents, (c) Chat Page

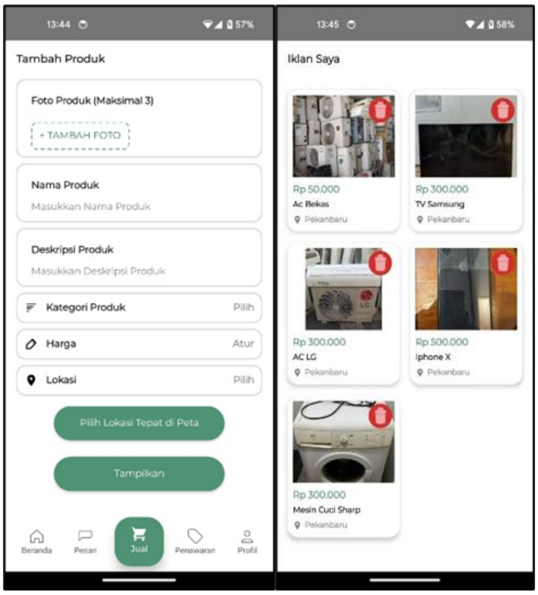

Figure 4 (a) Add Product page (b) Display Product

3.2 Usability Testing Result

Usability testing was conducted to evaluate the perceived ease of use, efficiency, visual attractiveness, and user satisfaction of the developed application. The evaluation involved 21 respondents representing potential Listers, such as university students and private employees, as well as e-waste technicians and local collectors representing Merchants. The usability instrument was a researcher-developed questionnaire adapted from common usability dimensions in human–computer interaction studies, including interface attractiveness, ease of use, task efficiency, feature clarity, and overall user satisfaction [15]. It did not fully adopt a standardized instrument such as SUS or UEQ, but was designed to reflect the specific workflow and user roles of the e-waste redistribution platform. The questionnaire used a five-point Likert scale, while the respondents' demographic profile is presented in Table 2 based on age group, professional background, and digital experience.

3.3 Functional Testing Result

The developed mobile application was evaluated through Black Box Testing to ensure that all system functionalities operate according to the defined requirements. This testing focused on validating input–output behavior without examining internal program structures. Table 3 present the result of black box testing. Based on the Black Box Testing results, all functional scenarios produced the expected outputs. This confirms that the core functionalities of the application have been successfully implemented and operate reliably.

Table 2. Demographic Profile of Usability Testing Respondents (n=21)

Demographic Category	Classification	Frequency (n)	Percentage (%)
Age Group	18 - 25 years old	12	57.1%
	26 - 35 years old	6	28.6%
	> 35 years old	3	14.3%
Professional Background	Students / University Students	10	47.6%
	Private / Public Employees	8	38.1%
	E-Waste Collectors / Technicians	3	14.3%
Digital Experience	**High** (Daily use of LBS/E-comm)	15	71.4%
	Medium (Weekly use)	4	19.1%
	Low (Rarely use digital platforms)	2	9.5%

Table 3. Blackbox Testing

No	Test Case	Expected Result	Result
1	User login (Lister, Merchant, Admin)	Users can log in successfully	Successful
2	User registration	Users can register an account	Successful
3	Viewing product list	Products and categories are displayed	Successful
4	Product upload (Sell Page)	Product data is saved and displayed	Successful
5	Chat communication	Users can send and receive messages	Successful
6	Merchant validation	Merchant can be verified	Successful
7	Profile management	User profile data can be updated	Successful
8	Product search (based on product's name, location)	Search results match user criteria	Successful
10	Admin merchant validation	Admin can approve or reject merchants	Successful
11	Admin report management	Admin can view product and merchant data	Successful

Table 4 presents the score intervals used to interpret respondents' perceptions based on the Likert scale, ranging from strongly disagree to strongly agree [16]. This formula calculates the ratio between the actual total score and the ideal total score (maximum score) to determine the percentage of system feasibility. It formulated as descriptive percentage technique to measure the eligibility of the system [17]. Score percentages are obtained to support the interpretation of usability evaluation outcomes. According to Table 5, P presents the number of questions.

Table 4. Score Interval

Interval Score	Interpretation
0% – 19.99%	Strongly Disagree (SD)
20% – 39.99%	Disagree (D)
40% – 59.99%	Neutral (N)
60% – 79.99%	Agree (A)
80% – 100%	Strongly Agree (SA)

Table 5. Usability Testing Result

Code	Question	Percentage
UEQ attractiveness		
P1	The application interface is attractive and modern.	89,5%
P2	The application gives a professional and trustworthy first impression.	89,5%
P3	The layout of the main screen is easy to understand	88,5%
Ease of use		
P4	The account registration process is clear and easy to follow.	94,2%
P5	Google account login works quickly and smoothly.	92,3%
P6	Logging in using email and password is easy.	93,3%
Ease of learning		
P7	The prototype instructions are clear and easy to follow.	93,3%
P8	The icons used in the application are easy to recognize.	93,3%
P9	I can easily find the page or feature I am looking for.	90,4%
Efficiency – Lister		
P10	The process of posting a new item is clear and straightforward.	91,4%
P11	The item detail form is easy to use.	90,4%
P12	Managing my posted items is easy.	92,3%
Efficiency – Merchant		
P13	The search feature works well and provides relevant results.	90,4%
P14	The product detail information is complete and helpful for decision-making.	95,2%
P15	Starting a chat with the seller is easy.	89,5%
Interaction		
P16	The chat feature is responsive and easy to use.	91,4%
P17	Notifications are helpful and informative.	91,4%
Satisfaction		
P18	The application runs smoothly without significant errors.	90,4%
P19	Overall, I am satisfied with using this application.	92,3%
P20	This application is useful for trading second-hand goods or services.	92,3%

The usability evaluation shows high user acceptance across all assessed aspects, with all questionnaire items scoring above 88% and falling within the “strongly agree” category. These results indicate that users perceived the application as intuitive, reliable, and effective for supporting second-hand electronic trading. Ease of use received the highest scores, above 92%, while ease of learning scored above 90%, showing that users could understand instructions, recognize icons, and access features easily.

Core features were also rated positively by both listers and merchants. Lister activities, including posting and managing items, scored above 90%, while merchant access to product details achieved the highest individual score of 95.2%, indicating its importance for decision-making. Communication and notification features further supported user engagement. The three key features were also validated through Blackbox testing: product upload functioned correctly, with user scores of 91.4% for process clarity and 90.4% for ease of use; location search produced accurate results, with a relevance score of 90.4%; and negotiation through chat worked properly, with scores of 89.5% for starting a chat and 91.4% for replying to messages. Overall, system stability and satisfaction scores above 90% confirm that the application is usable, stable, and suitable for further development toward real-world deployment.

4. CONCLUSION

This study demonstrates that a mobile-based C2C platform can support community-level e-waste redistribution by integrating user participation, merchant validation, negotiation, and Location-Based Services (LBS) into a circular-economy-oriented digital ecosystem. The main academic contribution of this study lies in the development of a user-centered redistribution model that bridges informal second-hand electronic trading and formal e-waste management practices. Rather than proposing a new optimization algorithm, the study shows how a standard LBS-based proximity matching mechanism can be adapted to improve the discoverability of nearby verified Merchants and reduce logistical barriers in e-waste redistribution.

Usability testing with 21 respondents produced an overall score of 91.5%, categorized as “Strongly Agree”. High scores across interface design, navigation, role-based features, communication, and user satisfaction confirm that the application is intuitive, easy to use, and well accepted as a platform for second-hand electronic goods trading. The Location-Based Search feature achieved a usability score of 90.4%, indicating that proximity-based matching helps address one of the main recycling barriers, namely the difficulty of locating nearby collectors. By supporting localized discovery, negotiation, and secure interaction between Listers and Merchants, the platform promotes circular economy pathways such as reuse, refurbishment, and material recovery.

Nevertheless, this study has several limitations. Although the sample size exceeded the minimum of 5–10 users commonly recommended for usability testing [20], the 21 respondents may not fully represent the wider population. In addition, long-term environmental impact and real operational performance were not yet evaluated. Future research should therefore involve larger-scale deployment, longitudinal environmental impact assessment, integration with logistics optimization and vehicle routing models, and performance evaluation in real operational environments.

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