

Smart Tech and Circular Economy for Waste to Learning Facilities

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ABSTRACT

Waste management facilities in developing countries often lack integration with environmental education, limiting opportunities for public engagement and sustainability learning. This study develops ISEEF-J (Integrated Smart Environmental Education Framework–Jeruklegi), a conceptual framework for supporting the transformation of TPST RDF Jeruklegi in Central Java, Indonesia, into a smart and community-driven environmental learning space. The framework integrates Augmented Reality (AR), Internet of Things (IoT), and Blockchain with circular economy principles and community-based participatory approaches. A **mixed-methods design** was employed through conceptual synthesis, benchmarking, a descriptive survey of 37 residents within a 5-kilometer radius, and three focus group discussions involving 15 participants. Survey responses were analyzed using descriptive percentages, while qualitative data were thematically examined using NVivo 14. **The findings** indicate strong stakeholder support for the proposed interventions, with 82% favoring AR-based environmental learning and 76% supporting IoT-based waste monitoring. Focus group findings further emphasized the importance of accessibility, community participation, infrastructure readiness, and hybrid digital–physical participation mechanisms. These findings informed the refinement of ISEEF-J into a modular framework linking smart technologies, environmental learning, circular economy practices, and participatory feedback. **The study contributes** a context-specific socio-technical framework for sustainable information systems design in semi-rural waste-management settings. The framework also provides potential pathways toward environmental education and responsible waste practices consistent with SDG 4 and SDG 12, although such contributions require future empirical evaluation through pilot implementation.

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1. INTRODUCTION

Indonesia generates over 175,000 tons of waste daily, and approximately 60% of this waste ends up in landfills without proper segregation or treatment. As one of the government's responses to this issue, the TPST RDF Jeruklegi facility in Cilacap was established to implement a Refuse-Derived Fuel (RDF) strategy, processing municipal waste into alternative fuel for cement industries. While the RDF facility successfully reduces landfill dependency and supports energy transition, it has not yet reached its full potential as a community learning and engagement center for environmental sustainability [1, 2].

Smart technologies offer complementary functions in environmental facilities: AR can provide educational content, IoT can monitor waste processes, and blockchain can support transparent, traceable records [3–5]. Circular-economy principles supply content on reuse, recycling, and eco-design, while participatory design connects these elements with local knowledge and access needs [6, 7].

Existing literature rarely combines smart, circular, and participatory components in a contextually grounded framework for the Global South, where infrastructure and community readiness vary. The proposed Eco Edu Park alongside TPST RDF Cilacap addresses this gap through a hybrid physical and digital environment for residents, learners, visitors, and public institutions [8]. Its proposed technologies and site design are intended to support circular-economy education and environmental stewardship [9–11].

Waste-management facilities can extend sustainability education beyond academic settings by linking explanations with observable infrastructure and processes [12]. AR and clean-energy examples may further support public engagement with environmental concepts [13, 14]. This approach treats facility operations, proposed digital explanations, and community activities as related parts of the learning environment rather than as separate interventions.

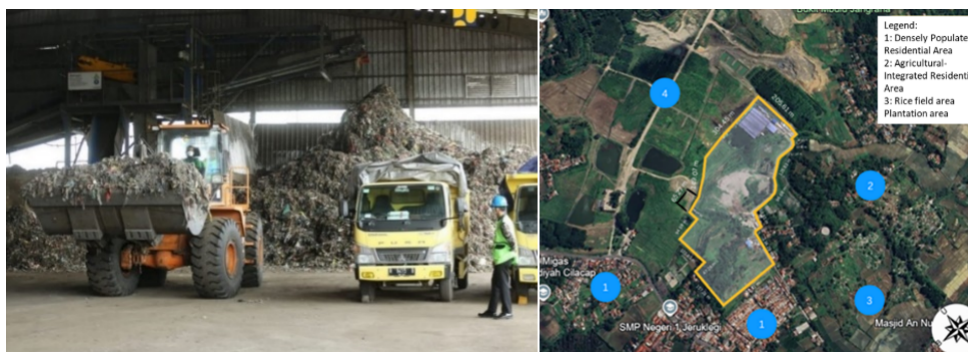


Figure 1. Integrated Waste Processing Facility and site location of Eco Edu Park

Figure 1 establishes the physical and operational context used to develop ISEEF-J. The existing RDF facility provides observable waste collection, sorting, processing, and recovery activities that could become the subject of on-site learning. Its location near the intended Eco Edu Park also supports a connection between facility operations and community education. At the same time, the semi-rural setting requires the framework to account for infrastructure availability, visitor access, digital literacy, and the need for both digital and non-digital participation channels. These site characteristics informed the selection of modular technologies, context-specific learning content, and staged implementation rather than an assumption that a complete smart system already exists.

Beyond its technological contribution, the ISEEF-J framework supports sustainability objectives through its alignment with SDG 4 (Quality Education) and SDG 12 (Responsible Consumption and Production). Through the integration of smart learning technologies, circular economy principles, and community participation, the framework provides a potential pathway for developing accessible environmental education and promoting responsible waste-management practices. However, these contributions represent conceptual implications rather than measured SDG achievements, requiring future implementation studies to evaluate their effectiveness in improving environmental literacy and sustainable behavior.

The main objective of this study is to design and contextually assess an integrated conceptual framework named ISEEF-J (Integrated Smart Environmental Education Framework - Jeruklegi) for supporting the development of TPST RDF Jeruklegi as a smart, community-based environmental education ecosystem. Specifically, this research aims to:

- Synthesize theoretical and empirical insights from strategic information systems (AR, IoT, Blockchain), circular economy education, and community-based participatory models to build a conceptual foundation for ISEEF-J.
- Benchmark international and local models of eco-education parks, smart waste systems, and circular learning initiatives to identify practices and contextual gaps that inform the framework design.
- Map stakeholder needs and participation potential at TPST RDF Jeruklegi through surveys and focus group discussions, in order to ensure that the framework is inclusive, locally relevant, and culturally responsive.
- Develop and propose a modular conceptual framework for ISEEF-J that integrates smart learning tools, sensor-based monitoring, feedback loops, and blockchain-based incentive mechanisms.
- Assess stakeholder perceptions of the framework's relevance, accessibility, and contextual suitability through descriptive survey findings and focus group feedback.

2. LITERATURE REVIEW

2.1. Strategic Information Systems and Sustainability

Strategic information systems may support environmental education within broader digital transformation and sustainability initiatives [15, 16]. At TPST RDF Jeruklegi, a municipal solid waste processing facility in Cilacap, Central Java, digital technologies could supplement waste-management operations with environmental learning activities. The proposed framework focuses on three technologies: Augmented Reality (AR), Internet of Things (IoT), and Blockchain. Each has a distinct potential role in public awareness, participatory learning, and environmental accountability [14, 17].

Augmented Reality (AR) can support on-site learning by superimposing digital content onto the physical environment. Through AR, visitors, particularly students, could interact with visualizations of the RDF process, from waste collection and sorting to shredding, drying, and pelletization [18, 19]. AR-enabled educational tours could include gamified modules and learning simulations tailored to different user levels. These functions may help explain waste cycles and circular-economy practices that are otherwise difficult to observe directly [6, 20].

Complementing AR, the Internet of Things (IoT) could support monitoring and visualization of environmental and operational indicators. Proposed sensors at selected points could collect data on waste input-output volumes, air quality, temperature, humidity, and RDF output efficiency [21]. Subject to infrastructure and data-quality testing, these records could be displayed through on-site and online dashboards for scenario-based learning, data interpretation, and sustainability planning. Such tools could also support future STEM and environmental studies activities [22–24].

The third strategic system, Blockchain, plays a unique role in building transparency and incentivizing community engagement in waste education ecosystems [25]. Blockchain technology can be used to record waste contributions by households, schools, or communities, with digital tokens or rewards granted for proper waste sorting and delivery. Additionally, it can be used to issue immutable, verifiable certificates for participants in educational programs, workshops, or clean-up campaigns. More broadly, Blockchain facilitates traceability of circular economy practices, helping track the lifecycle of recycled materials and RDF energy generation, and reinforcing trust in the learning ecosystem through decentralized accountability [26, 27].

The proposed integration of AR, IoT, and Blockchain at TPST RDF Jeruklegi defines the technological layer of ISEEF-J. AR would provide process visualization, IoT would supply operational and environmental data, and Blockchain could maintain traceable participation records. Their coordinated use is intended to support experiential and participatory learning, but effects on environmental literacy, decision making, and community participation require pilot evaluation.

Integration also enables exchange among the components. IoT records could provide current examples for dashboard and AR explanations, participation records could connect eligible activities with incentives, and community feedback could guide later content revisions. This coordination distinguishes ISEEF-J from placing unrelated technologies at the same site. The detailed implementation roles of these proposed components are presented with Figure 6.

2.2. Community-Based Participatory Approaches in Sustainability

Community-based Participatory Approaches (CBPA) position local stakeholders as co-creators rather than passive beneficiaries of sustainability initiatives [28, 29]. At Jeruklegi, this approach can connect environmental education with local knowledge, shared responsibility, and continued participation [30].

The surrounding community, which includes households, schools, small-scale enterprises, and local leaders, plays a central role in the effectiveness of waste segregation, collection, and delivery to the RDF facility. Community engagement is not only essential for supplying a clean and sorted waste stream, but also for embedding sustainable behavior into daily practices [31]. Through participatory methods such as focus group discussions, local workshops, co-design of educational modules, and school-based outreach, TPST RDF Jeruklegi can foster inclusive environmental stewardship. For instance, training programs on waste separation and upcycling, combined with storytelling from local waste workers, can deepen awareness while respecting and integrating indigenous knowledge and lived experiences [32, 33].

Participation in planning and evaluating AR, IoT, and other educational content can align the proposal with local capacities and encourage ownership. Student projects, youth volunteering, and community science may support intergenerational learning while allowing residents to document waste challenges and propose locally appropriate responses.

Different participation formats serve different purposes. School activities can introduce waste separation and material cycles, workshops can draw on the practical experience of facility workers and recyclers, and community forums can identify concerns about access or incentives. Storytelling, demonstrations, and co-designed modules may also translate technical information into locally familiar examples. These activities create opportunities for residents to contribute to both the substance and delivery of environmental education rather than only receive finished content.

The participatory model also supports social inclusion by allowing waste pickers, informal recyclers, and women in low-income households to contribute knowledge and access training, tools, and incentives. These groups may identify barriers involving language, schedules, device access, or reward design that are not evident during technical planning. Hybrid rewards can recognize local contributions without requiring universal digital access [3].

Participation should continue beyond initial consultation. Community representatives could review learning materials, identify accessibility problems during pilots, and advise on AR content, dashboard displays, and incentive rules. CBPA therefore provides the social foundation for adapting ISEEF-J technologies and learning activities to local conditions while reducing the risk of a top-down implementation.

Continued participation may also support accountability by providing a local channel for reporting operational, educational, or access problems after a pilot begins.

2.3. Circular Economy and Environmental Learning

The concept of a Circular Economy (CE) offers a transformative model for rethinking waste not as an endpoint, but as a valuable resource that can be reintegrated into new production and learning cycles. In the context of TPST RDF Jeruklegi, located in Cilacap, Central Java, Indonesia, circular economy principles are not only applicable to material recovery and waste processing, but also serve as a foundation for environmental learning and sustainability education. This dual-purpose transformation where waste facilities become centers of both recycling and knowledge demonstrates how CE can be aligned with educational innovation and community empowerment [34].

At TPST RDF Jeruklegi, the facility's core operation focuses on converting organic and inorganic waste into Refuse-Derived Fuel (RDF), which is then utilized by nearby industries as an alternative energy source [35]. While this aligns with CE objectives of reducing landfill dependency and closing energy loops, the potential for environmental learning integration has remained largely untapped. By embedding CE principles into the design of educational experiences such as through learning stations, digital simulations, and interactive exhibits, the facility can evolve into a living classroom that illustrates how materials flow through circular systems, from collection and segregation to processing and reuse [36, 37].

AR could visualize decomposition timelines and material life cycles, while tested IoT data could explain sorting efficiency and contamination. Combined with community-driven curricula, these tools could support instruction on the "5Rs" Refuse, Reduce, Reuse, Recycle, and Recover and connect operational data with reflection, without implying that the tools are already deployed [27, 38].

The learning design could compare different points in the waste hierarchy. Visitors might examine

which materials can be refused or reused, how separation affects recycling, and why residual waste may enter RDF production. This would place energy recovery within a broader circular-economy explanation rather than present it as the only solution.

Compared with the models reviewed such as smart eco-campus systems that focus mainly on IoT monitoring, or eco-park programmes that rely on traditional educational displays, ISEEF-J introduces three clear distinctions. First, it synchronizes AR, IoT, and blockchain as an integrated learning system rather than using them as isolated technologies. Second, it employs a hybrid digital–physical incentive approach to include participants with low digital literacy. Third, it adopts a participatory co-design process that positions the community as active contributors instead of passive visitors. These elements together show how ISEEF-J addresses the limitations observed in previous models and advances a more inclusive and educationally oriented framework for semi-rural RDF contexts.

3. METHODS

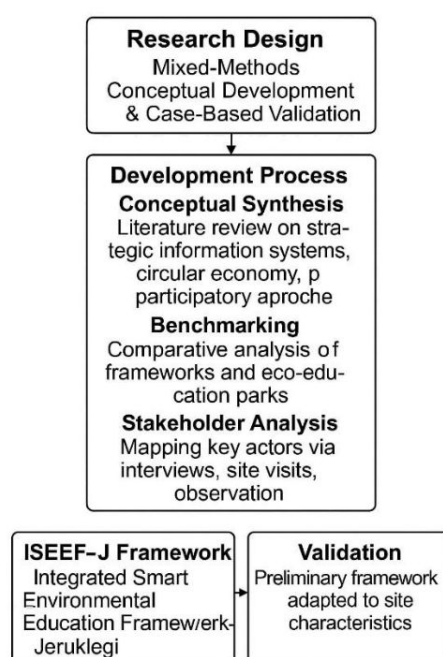


Figure 2. Research Methodology for developing ISEEF-J

Figure 2 summarizes the research sequence from conceptual synthesis and stakeholder assessment to framework development. This mixed-methods study combines conceptual synthesis with an exploratory stakeholder assessment of a semi-rural waste-management facility. The survey describes perceptions, environmental awareness, and support for proposed interventions, while focus group discussions and observation provide context about stakeholder priorities and technology adoption. Together with the reviewed literature, these sources inform the framework but do not provide technical or outcome validation.

The ISEEF-J (Integrated Smart Environmental Education Framework – Jeruklegi) was developed through a structured, multi-stage process to design a contextually relevant, technology-integrated model for supporting a participatory educational space at TPST RDF Jeruklegi. The process began with a literature review on strategic information systems (AR, IoT, Blockchain), circular economy models, environmental education practices, and community-based participation. Combined with benchmarking and stakeholder analysis, these insights informed a preliminary, modular framework that proposes AR learning tools, IoT-based displays, blockchain-supported eco-incentive tracking, and community feedback mechanisms. The resulting design reflects the theoretical and socio-technical considerations identified in the study.

The quantitative phase involved a structured survey of 37 residents within a 5-kilometer radius of

the facility, gathering data on demographics, environmental awareness, waste-management perceptions, and expectations for the Eco Edu Park. Responses were summarized using descriptive percentages. The survey is treated as exploratory stakeholder feedback rather than a representative estimate of the wider population.

The qualitative investigation involved three focus group sessions with 15 participants. The available study records do not provide a reliable participant breakdown by stakeholder category; therefore, the analysis does not claim a separate expert-validation stage. The discussions were coded using NVivo 14 qualitative analysis software to identify themes concerning community participation, technology adoption, accessibility, and pedagogical value. Comparing these themes with the survey and literature informed the interpretation. The empirical work assesses perceived relevance and contextual suitability rather than the technical performance of an implemented system.

4. RESULTS AND DISCUSSION

4.1. Demographic Insights and Stakeholder Diversity

The survey respondents represented stakeholders from different age groups, genders, and professional fields. Participants aged 18–30 accounted for 42% of the sample, indicating substantial representation of younger respondents who may be familiar with mobile applications and interactive learning formats. This age profile supports consideration of youth-oriented activities while also emphasizing the need for interfaces and non-digital alternatives that remain accessible to older visitors. Gender representation was 51% female and 49% male, providing a relatively balanced basis for considering gender-inclusive program design. These descriptive characteristics do not establish population representativeness, but they help identify accessibility and engagement requirements for the proposed Eco Edu Park.

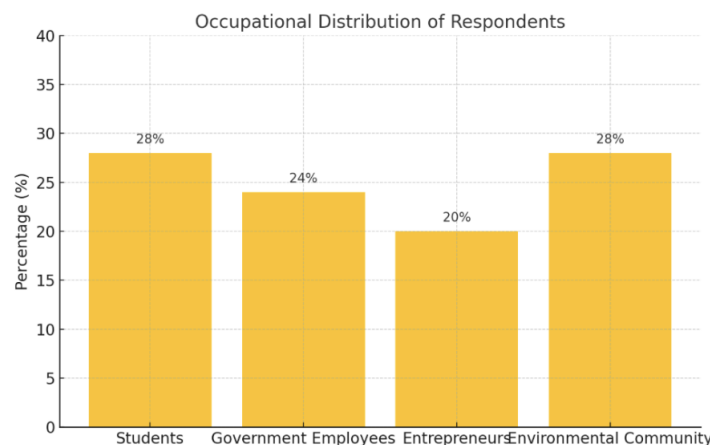


Figure 3. Occupational Distribution of Respondent

As shown in Figure 3, professional backgrounds of respondents were distributed across four key groups: students (28%), government officials (24%), business owners (20%), and environmental group members (28%). This occupational mix suggests that the Eco Edu Park could support student-focused workshops, policy discussions for government representatives, showcases of sustainable business innovations, and collaboration among environmental advocates. Students may contribute learning preferences and volunteer participation, government representatives may connect the proposal with local planning, business owners may identify circular-economy opportunities, and environmental groups may support outreach and community monitoring. These complementary roles could facilitate intersectoral partnerships and community-driven environmental stewardship. Programming should therefore accommodate the distinct interests and levels of technical familiarity of each stakeholder group while maintaining consistent sustainability messaging and shared learning objectives.

The diversity represented in the survey also supports a participatory approach to future development. Rather than applying a single communication or engagement model, pilot activities could combine visual demonstrations, facilitated discussions, practical workshops, and accessible digital content. Feedback from different age, gender, and occupational groups could then be used to identify whether particular interfaces,

learning materials, or participation mechanisms create unintended barriers. This iterative process would help translate the demographic findings into design decisions while recognizing that broader community testing remains necessary before the framework is implemented at scale.

4.2. Community Support and Participation

The community survey indicates substantial support for the proposed Eco Edu Park project at TPST RDF Cilacap, with 78% of participants strongly supporting its development. In addition, 81% of respondents expected the park to enhance environmental awareness, and 65% believed it could reinforce local identity and community pride, as summarized in Figure 4. These findings represent stakeholder expectations regarding the proposed park rather than evidence of its actual effectiveness.

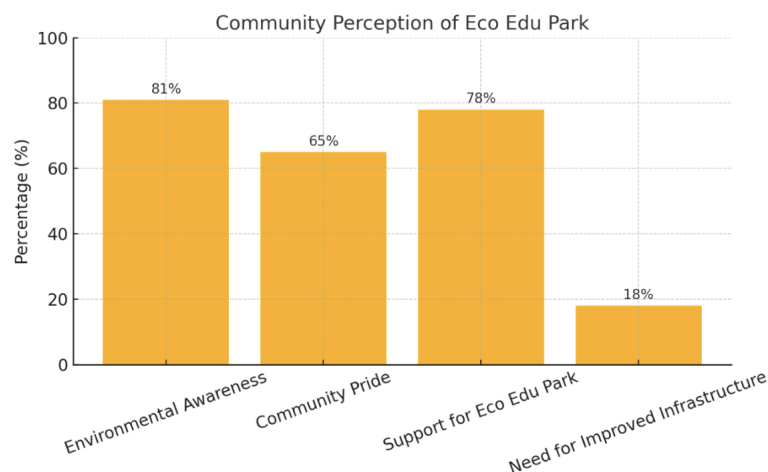


Figure 4. Community Perception of Eco Edu Park

FGD participants supported the park's educational potential and valued proposed nature trails, signage, digital information stations, and environmental art as possible learning and community-building resources. They associated these features with opportunities to explain waste processes in a setting accessible to families, students, and community groups.

Participants also viewed the proposed physical and digital elements as complementary: site-based activities could provide direct experience, while displays and guided explanations could make technical processes easier to interpret.

Participants also advocated free or low-cost admission, particularly for students and economically disadvantaged groups. This preference reflects approaches that balance environmental objectives with social equity and community-centered design [39, 40]. Planning should therefore address financial accessibility alongside the park's educational and environmental purposes and consider how operating costs would affect continued public access.

The findings indicate community support for collaborative governance, with participants recommending partnerships involving youth groups, educational institutions, and environmental organizations. Participants associated this approach with operational continuity, local relevance, and shared ownership. Studies by [2, 41] similarly identify inclusive planning as an important condition for circular-economy initiatives in urban development. Research by [42] also links community co-creation with digital innovation and environmental management. These findings support a shift from centralized planning toward locally informed development consistent with circular-economy principles.

The chart reiterates that 81% expected greater environmental awareness, 65% anticipated stronger community identity, and 78% strongly supported the proposal. These expectations are consistent with research describing public green spaces as potential settings for environmental learning and interaction [43, 44]. They describe anticipated benefits rather than observed changes after implementation.

Nevertheless, 18% of participants identified infrastructure deficiencies as a concern, indicating that the proposal must be supported by practical amenities. This observation is consistent with research describing physical infrastructure as an important complement to participatory design in sustainability initiatives [45].

12	Ecotourism	Moderate	Environmental Tourism	Refers to integration of eco-tourism elements in the park's function.
13	Facilities	Low to Moderate	Service & Access	Shows consideration for supportive infrastructure (toilets, cafes, etc.).
14	Sustainability	Low	Sustainability Awareness	While the word may not appear often, it's conceptually present in related terms.

Table 1 organizes the recurring terms by estimated frequency, thematic category, and design interpretation. Keywords such as visitors, needs, and education support a user-centered orientation for the proposed Eco Edu Park, with needs emphasizing accessibility for different groups and education supporting workshops, hands-on activities, and community programs. Operational terms such as waste system, TPST, and facilities connect the learning proposal to the existing waste-management setting, while less frequent terms such as sustainability and ecotourism remain conceptually relevant but should not be interpreted as measured outcomes. Overall, the NVivo findings indicate that stakeholders view the Eco Edu Park as a potential setting for sustainability advocacy, socio-technical innovation, and inclusive community development. Survey and FGD feedback also indicates that basic amenities remain important alongside proposed technologies such as AR exhibits and smart information systems. Participants identified clean restrooms, shaded seating, and accessible food kiosks as requirements for a comfortable learning environment, especially for families and older adults. These responses suggest that environmental learning at the site would depend on accessibility, spatial comfort, opportunities for social interaction, and technology.

4.4. Theoretical Contribution of ISEEF-J

The principal theoretical lens for ISEEF-J is the sociotechnical perspective, which treats outcomes as dependent on the fit among technologies, users, infrastructure, organizational practices, and the local environment [34]. Technology acceptance and participatory governance provide supporting perspectives. Technology acceptance directs attention to perceived usefulness and accessibility [29], while participatory governance emphasizes co-design, shared ownership, and continued community involvement [30, 42].

The theoretical gap addressed by ISEEF-J is the limited integration of these dimensions in semi-rural waste-learning facilities. Existing approaches commonly emphasize a single technology, operational monitoring, or environmental education without specifying how infrastructure readiness and community participation shape the coordinated use of AR, IoT, and blockchain. ISEEF-J addresses this gap by linking each proposed technical function to a social and organizational condition: AR content must be accessible to different learners, IoT monitoring depends on connectivity and staff capacity, blockchain incentives require inclusive digital and physical options, and all components are revised through participatory feedback.

The findings support this configuration at the level of stakeholder perception. Support for AR and IoT indicates perceived usefulness but not actual adoption; reported digital-literacy and connectivity concerns indicate sociotechnical constraints; and preferences for community involvement and hybrid incentives support participatory adaptation. The contribution is therefore a context-specific application and integration of existing theoretical perspectives rather than a new general theory or evidence of system effectiveness.

4.5. Process Development of ISEEF-J

The development of the ISEEF-J (Integrated Smart Environmental Education Framework – Jeruklegi) followed a sequential, multi-layered process emphasizing theoretical rigor and contextual relevance. It began with a conceptual synthesis through an extensive literature review on strategic information systems (AR, IoT, Blockchain), environmental education, circular economy principles, and participatory community approaches. This stage established the framework's theoretical foundation and identified the key components and their interconnections.

The next phase involved benchmarking against global and Indonesian cases of smart waste management and eco-education environments. This comparison highlighted gaps in existing models, particularly in integrating smart technology with education and community engagement areas often fragmented or misaligned with semi-rural contexts like TPST RDF Jeruklegi. The third phase consisted of stakeholder analysis on-site, using interviews, focus group discussions, and field observations with facility managers, educators, officials, workers, NGOs, and local residents. This revealed strong community interest in environmental learning, alongside infrastructural constraints and the need for accessible, inclusive technologies.

By synthesizing insights from these stages, the research team developed the first version of the modular ISEEF-J framework. It combines proposed AR learning tools, IoT-based monitoring, blockchain-supported

eco-incentives, and participatory feedback loops tailored to the reported operational and social conditions of TPST RDF Jeruklegi. The design is therefore conceptually grounded and informed by stakeholder perspectives, while its practical performance remains to be evaluated through implementation.

The proposed components have distinct implementation roles. The AR module would use mobile devices or tablets and marker-based triggers at selected RDF stations to load three-dimensional animations or guided explanations. The IoT module would use low-cost load, temperature-humidity, and particulate sensors connected through Wi-Fi or LoRaWAN microcontrollers to a cloud dashboard. The blockchain component is proposed as a lightweight registry on an energy-efficient or private chain for recording eligible participation and learning activities. Digital rewards would be paired with printed or physical alternatives for users without suitable devices. These specifications remain subject to technical testing and local adaptation.

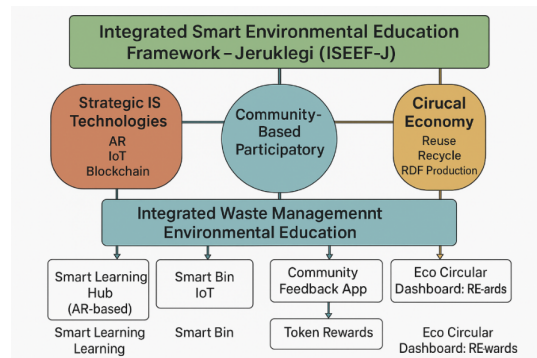


Figure 6. Proposed Conceptual Architecture of ISEEF-J

Figure 6 presents a proposed logical architecture with three related flows. First, in the data flow, smart-bin IoT devices would collect waste volume, type, and collection-status records. Wi-Fi or LoRaWAN connectivity would transmit those records to the Eco Circular Dashboard, where authorized facility staff would check and interpret them. Selected dashboard information would then be supplied to the Smart Learning Hub for educational display. Second, in the participation and reward flow, validated records of eligible activities would pass from the dashboard to the proposed blockchain registry. The Community Feedback App would use the registry to communicate digital rewards, while printed or physical alternatives would remain available for users without digital access. Third, in the learning and feedback flow, visitors would interact with AR content and dashboard information through the Smart Learning Hub, then submit comments through digital or non-digital channels. Facility staff and community representatives would use this feedback to revise learning content, access arrangements, and implementation decisions. The arrows and component relationships in Figure 6 should therefore be read as proposed data exchanges and user interactions, not as a deployed, simulated, or performance-tested system.

4.6. Stakeholder Assessment of ISEEF-J Through Focus Group Discussion

To assess the perceived relevance and contextual suitability of ISEEF-J, three Focus Group Discussion (FGD) sessions were conducted with 15 participants associated with TPST RDF Jeruklegi. The available records do not support a reliable breakdown by stakeholder category or a separate expert-validation claim. The discussions examined the proposed technology integration and its alignment with local needs and capacities. This process constitutes stakeholder-based conceptual assessment rather than technical testing of the proposed system.

Table 2. Stakeholder assessment and implementation priorities for the proposed ISEEF-J framework

Component	Stakeholder Feedback	Issues/Concerns	Recommendations	Priority
Overall Framework	Support for transforming the RDF facility into an educational space.	Practical demonstration and continued stakeholder involvement are needed.	Use participatory implementation and maintain feedback mechanisms.	High: establishes the basis for implementation.

Augmented Reality (AR)	Considered engaging and useful for youth education.	Content requires localization for different learning levels.	Develop multilingual, age-appropriate modules.	Medium: timing depends on visitor needs.
Internet of Things (IoT)	Considered useful for monitoring and data display.	Digital infrastructure and staff capacity may be limited.	Provide training and assess electricity and internet availability.	High: readiness is required before deployment.
Blockchain Incentive System	May encourage environmentally responsible behavior.	Accessibility may be limited for older or low-technology users.	Use digital and printed reward options.	Medium: supports engagement but is not a core operational requirement.
Community Participation	Participants emphasized continued engagement.	A top-down approach could limit local ownership.	Form an advisory group and involve the community in content development.	Critical: required throughout implementation.

Table 2 presents qualitative sequencing judgments rather than statistical risk scores: community participation is critical, governance and IoT readiness are high priorities because they depend on planning, infrastructure, and staff capacity, and AR and blockchain are medium priorities that may follow foundational preparation. Participants supported using the RDF facility for environmental education, viewing AR as useful for visualizing waste processes and real-time monitoring as potentially beneficial for learning and transparency. A future pilot should assess digital literacy and training, electricity reliability, internet and data-transfer options, and age-appropriate, multi-format interfaces; these are information needs rather than evidence of current readiness or technical feasibility. Blockchain incentives could reward waste sorting, volunteering, and workshop participation, but limited smartphone or digital-wallet access supports combining digital tokens with printed or physical rewards. The FGD also favored community involvement in learning materials and digital content rather than top-down implementation. Overall, the framework was perceived as locally relevant, provided that equitable access, digital inclusion, cultural sensitivity, and continued stakeholder participation are maintained.

4.7. Replication and Local Adaptation Roadmap

ISEEF-J is intended to be modular so that its educational, technological, and participatory components can be adapted to different institutional and community settings. However, application at another RDF facility, educational institution, or eco-park should follow a staged process rather than direct duplication. Differences in waste-management operations, infrastructure, staff capacity, learner characteristics, accessibility, funding, and community priorities may affect which components are appropriate and how they should be implemented. Table 3 therefore presents a proposed roadmap that begins with local readiness and stakeholder assessment before technology selection and participatory co-design. It then moves through limited pilot testing, training, operation, and evaluation. Advancement between stages should depend on completion of the stated output or decision gate so that implementation decisions remain responsive to local evidence and constraints.

Table 3. Proposed roadmap for replication and local adaptation of ISEEF-J

Stage	Focus	Main activities	Output or decision gate
1	Site-readiness assessment	Document waste processes, learning opportunities, safety conditions, electricity, connectivity, devices, accessibility, and staff capacity.	Readiness profile and list of constraints.
2	Stakeholder mapping	Identify operators, educators, community groups, learners, government actors, and groups at risk of digital exclusion; define governance roles.	Stakeholder map and participation plan.
3	Technology selection	Match AR, IoT, blockchain, dashboard, and non-digital options to local needs, infrastructure, cost, maintenance capacity, and data requirements.	Approved minimum pilot configuration.
4	Participatory co-design	Develop learning content, interfaces, incentives, accessibility measures, and feedback channels with intended users.	Locally reviewed pilot materials and procedures.

5	Pilot testing	Test a limited set of functions for usability, data reliability, accessibility, safety, and operational fit.	Pilot evidence and a decision to revise, extend, or stop.
6	Training and operation	Train staff and community facilitators; assign data, maintenance, content, safeguarding, and support responsibilities.	Operational roles, training records, and maintenance plan.
7	Evaluation and adaptation	Evaluate participation, usability, learning perceptions, system reliability, access barriers, and costs; revise components before incremental expansion.	Local adaptation report and evidence-based scaling decision.

This roadmap treats scalability as an evidence-dependent, locally managed process. A site may adopt only components that address its educational and operational needs and satisfy readiness conditions. AR learning may proceed without blockchain incentives, while non-digital participation may be prioritized where device access or digital literacy is limited. IoT monitoring should advance only after assessing electricity, connectivity, data quality, maintenance capacity, and staff responsibilities. Component selection should also consider safety, affordability, and compatibility with existing facility workflows. Beginning with the smallest workable configuration allows essential functions to be tested before further investment. This modular approach retains the integration of environmental education, technology, and community participation without requiring an identical configuration at every site.

Effective replication also requires clear local governance. Facility managers, educators, community representatives, and government actors should agree on decision-making, data management, content review, maintenance, safeguarding, and responses to participant feedback. Documented responsibilities can support continuity when staff, funding, or technical conditions change. Governance arrangements should specify when performance, access issues, and community concerns will be reviewed and who may revise or suspend a component. Regular review can also keep educational content aligned with changing waste practices, learner needs, and community priorities. Local partnerships should therefore give each component an identified owner and a practical continuity plan.

Evaluation at each stage should document enabling conditions and barriers, including usability, accessibility, participation, reliability, learning perceptions, and cost. Components that perform adequately in a limited pilot may be expanded incrementally, while unsuitable elements should be revised, replaced, or omitted. Results should inform the next decision gate and be shared with participating institutions and community representatives. Recording why components were retained or changed can also provide practical guidance for later implementation at comparable sites. The roadmap therefore supports replication through structured local adaptation rather than transferring the Jeruklegi framework unchanged.

5. MANAGERIAL IMPLICATIONS

The findings guide managers, policymakers, and practitioners considering waste-management facilities as learning environments. ISEEF-J proposes AR for education, IoT for operational transparency, and blockchain for participation incentives. Implementation should follow the staged roadmap through readiness assessment, stakeholder mapping, a minimum pilot, training, and evaluation before expansion. Plans and budgets should assign responsibility and resources for maintenance, data, content, accessibility, staff capacity, and community feedback, while non-digital alternatives should protect inclusive participation. Partnerships among schools, communities, facility operators, and government can distribute responsibilities and connect environmental education with waste-management planning. Evaluation should examine usability, participation, access barriers, reliability, learning perceptions, costs, and workflow effects. Evaluation should examine usability, participation, access barriers, reliability, learning perceptions, costs, and workflow effects.

6. CONCLUSION

This study developed ISEEF-J, a conceptual and integrative framework for supporting the transformation of TPST RDF Jeruklegi in Central Java, Indonesia, into a participatory environmental learning space. The framework integrates Augmented Reality (AR), Internet of Things (IoT), Blockchain, circular economy principles, and community-based participation within a socio-technical design. Through conceptual synthesis, benchmarking, stakeholder survey, and focus group discussions, the study identified the technological, social, and infrastructural conditions that should be considered when developing a smart learning environment around

a waste-processing facility. The findings indicate substantial stakeholder interest in the proposed approach, while also highlighting the importance of accessibility, digital inclusion, infrastructure readiness, staff capacity, and continued community involvement.

The main contribution of ISEEF-J lies in specifying how smart technologies can be coordinated with social and organizational conditions rather than implemented as isolated technical components. AR is positioned to support experiential visualization and environmental learning, IoT to provide operational and environmental information for educational purposes, and Blockchain to support traceable participation and incentive mechanisms. The framework further incorporates hybrid digital–physical participation to accommodate differences in digital access and literacy. These contributions remain conceptual and stakeholder-informed because the proposed system has not yet been deployed or technically evaluated. Therefore, the findings should be interpreted as evidence of perceived relevance and contextual suitability rather than evidence of technological effectiveness, behavioral change, or environmental performance.

ISEEF-J also provides a practical basis for staged implementation through site-readiness assessment, stakeholder mapping, technology selection, participatory co-design, pilot testing, training and operation, and evaluation with local adaptation. Its orientation toward environmental learning and responsible waste practices provides potential relevance to SDG 4 and SDG 12, while these contributions should not be interpreted as measured SDG achievements. Future research should conduct pilot implementation and evaluate usability, learning outcomes, environmental behavior, system reliability, accessibility, operational performance, and cost across different socio-geographic settings. Such evidence would strengthen the validation and scalability of ISEEF-J beyond the Jeruklegi context.

7. DECLARATIONS

7.1. About Authors

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7.2. Author Contributions

Conceptualization: SB; Methodology: AM; Software: EP; Validation: RS and AM; Formal Analysis: FF and DG; Investigation: RS; Resources: AM; Data Curation: AM; Writing Original Draft Preparation: EP and FF; Writing Review and Editing: EP and DG; Visualization: AM; All authors, SB, AM, EP, RS, FF, and DG, have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The aggregate percentages used in this study are reported in the article. The respondent-level survey dataset and detailed FGD participant-composition records are not available.

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7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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