SUDEIJ
Sustainable Urban Development and Environmental Impact Journal
SUDEIJ 3(2): 137–158
ISSN 3062-8997

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Urban gold mining credit: Designing a carbon credit mechanism for gold recovery from electronic waste

Beckham Napitupulu[1,*], Aidatul Fitriyah[2]
[1] *Public Sector Accounting, Accounting Program, Politeknik Keuangan Negara STAN, South Tangerang, Banten 15222, Indonesia;*
[2] *Department of English Language and Literature, Faculty of Humanities, Universitas Airlangga, Surabaya, East Java 60286, Indonesia.*
*Correspondence: beckham_4131230349@pknstan.ac.id

Received Date: April 6, 2026 Revised Date: August 27, 2026 Accepted Date: August 27, 2026

ABSTRACT

Background: Indonesia generates 1.9 million tons of e-waste annually, with a 20% recycling rate. Printed circuit boards contain 240–340 grams of gold per ton, 300 times higher than natural ore. Urban mining recovers resources while reducing emissions, yet economic mechanisms remain underdeveloped. Indonesia's carbon credit infrastructure (SRN-PPI and IDX Carbon) provides potential to monetize environmental benefits. **Methods:** Research employs qualitative policy design with Life Cycle Assessment (LCA) following ISO 14040/14044. Comparative regulatory analysis examines how international carbon credit methodologies (Verra AMS-III.BA, Gold Standard) adapt to SRN-PPI requirements. Primary data includes Ministry regulatory documents and IDX Carbon specifications. Secondary data comprises peer-reviewed literature (2012–2025) on LCA, carbon pricing, and urban mining. Economic analysis uses discounted cash flow modeling with a 10-year projection and sensitivity analysis. **Findings:** LCA demonstrates urban gold mining from e-waste achieves 13,041 kg CO_2-equivalent per kilogram gold savings, 86.9% reduction versus the primary mining baseline of 15,000 kg CO_2-eq per kilogram. The hybrid carbon credit protocol adapts Verra methodology to SRN-PPI compliance, maintaining methodological integrity. Operational pathway from development through validation, registration, monitoring, and verification is clearly mapped. Economic analysis shows a 1,000-ton-per-year facility generates a baseline net present value of IDR 108 billion (USD 5.95 million); carbon credit revenue adds IDR 274 million (USD 15.105) annually, while green gold premium significantly boosts the NPV to Rp 130 billion (+20.4%). **Conclusion:** Urban gold mining with integrated carbon credits and ESG-aligned bullion banking creates a viable pathway for Indonesia to formalize e-waste management and reduce emissions. Multi-stakeholder coordination is essential. **Novelty/Originality of this article:** First comprehensive integration of LCA, carbon credit protocol adapted to Indonesia's SRN-PPI, and green gold market analysis for urban precious metal recovery from e-waste in Southeast Asia.

KEYWORDS: carbon credit; e-waste recycling; environmental, social, and governance investment; green gold; urban mining.

1. Introduction

The global gold industry faces an increasingly urgent environmental paradox. While conventional mining operations continue to extract resources through energy-intensive processes and generate substantial carbon emissions, a largely overlooked urban gold reservoir exists in the form of electronic waste (e-waste). Life Cycle Assessment (LCA) studies consistently show that primary gold production from hard-rock mining generates a

Cite This Article:
Napitupulu, B. & Fitriyah A. (2026). Urban gold mining credit: Designing a carbon credit mechanism for gold recovery from electronic waste. *Sustainable Urban Development and Environmental Impact Journal, 3*(2), 137-158. https://doi.org/10.61511/sudeij.v3i2.2026.3479

Copyright: © 2026 by the authors. This article is distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

carbon footprint ranging from 12,200 to 18,000 kg CO_2-eq per kilogram of gold produced, with grinding and off-gas treatment operations contributing to the majority of emissions (Kadivar et al., 2023; Norgate & Haque, 2012). More recent data from integrated metallurgical operations report even higher emission intensities, reaching 15,400 kg CO_2-eq per kilogram of gold when accounting for the entire supply chain from mining to refining (Aurubis, 2024). These figures underscore the heavy environmental burden associated with meeting global gold demand through conventional mining.

Indonesia presents a particularly striking example of this paradox. As one of Southeast Asia's largest producers of electronic waste, the country generates approximately 1.9 million tons of e-waste annually, yet achieves a recycling rate of less than 20 percent (Firmansyah et al., 2025; United States - ASEAN Smart Cities Partnership (USASCP), 2024). This low recovery rate results in the loss of valuable metal resources to landfills or informal recycling channels, posing severe environmental and health risks. Printed circuit boards (PCBs) from used computers and mobile devices contain gold concentrations ranging from 240 to 340 grams per ton, which is 50 to 300 times higher than the average gold ore grade in natural deposits (Phogat et al., 2025; Xavier et al., 2023). From a resource-efficiency perspective, this represents an urban mine of precious metals waiting to be systematically exploited through environmentally responsible methods.

The technology for recovering gold from e-waste through hydrometallurgical processes has matured significantly over the past decade. Comparative LCA studies show that hydrometallurgical recovery achieves extraction efficiencies exceeding 90 percent while producing substantially lower emissions than primary mining operations (Li et al., 2019; He et al., 2023). The critical difference lies in the elimination of energy-intensive stages inherent in primary mining, including excavation, comminution of large volumes of rock, and tailings management. By processing materials that are already concentrated in metal content, the urban mining pathway reduces energy requirements by more than 90 percent relative to conventional mining (Cespi et al., 2025). This translates to a carbon-emissions profile for e-waste gold recycling estimated at 50 to 150 kg CO_2-eq per kilogram, representing a reduction of 99.0 to 99.8 percent compared to the primary production baseline.

Despite its attractive environmental advantages, the economic incentive structure for transitioning from conventional mining to urban mining remains underdeveloped. Indonesia has established a foundational carbon-pricing platform with the launch of IDX Carbon in September 2023, which operates within the regulatory framework of the National Registry System for Climate Change Control/*Sistem Registri Nasional Pengendalian Perubahan Iklim* (SRN-PPI) overseen by the Ministry of Environment and Forestry (Sudjonno et al., 2024; Sunanda et al., 2025). By mid-2025, this carbon market had facilitated the trading of 1.6 million tons of CO_2-equivalent in Greenhouse Gas Emission Reduction Certificates/*Sertifikat Pengurangan Emisi Gas Rumah Kaca* (SPE-GRK) (Hannany & Priambodo, 2025). However, registered projects remain concentrated in conventional sectors such as renewable energy generation, palm-oil mill biogas, and municipal solid-waste management. The potential for urban mining from e-waste to generate verified carbon credits has not been systematically explored in Indonesia's regulatory and market infrastructure.

A theoretical framework linking circular-economy principles with carbon-emission reduction provides a conceptual foundation for addressing this gap. Empirical evidence from 29 European countries shows that circular-economy interventions produce synergistic effects with carbon-mitigation efforts, with minimal offset behavior (Hailemariam & Erdiaw-Kwasie, 2023; Wang et al., 2024). Extending these principles to the precious metals sector requires adaptation to the sector's specific characteristics, including high material value, strict purity requirements, and the existence of an established global bullion market with its own certification and traceability standards.

The regulatory landscape for carbon-credit mechanisms in resource-dependent sectors is evolving rapidly, with an emerging framework for integrating environmental costs into economic decision-making (Mirzehi & Moradi Afrapoli, 2024). Carbon-pricing mechanisms,

whether implemented through carbon taxes or emissions-trading systems, generate government revenues that can be allocated toward expanding renewable-energy capacity (Riyono et al., 2025). More fundamentally, the mining sector's shift toward integrating renewable energy and lowering its carbon footprint hinges on the presence of financial instruments that can translate emission reductions into monetary value (Enemuo & Ogunmodimu, 2025). Indonesia's carbon-pricing framework combines sectoral applications covering energy, waste management, and industrial processes, setting a precedent for expanding coverage to urban-mining activities (Sudjonno, 2024).

A critical review of the existing literature reveals three significant research gaps that limit the operationalization of carbon-credit mechanisms for gold urban mining in Indonesia. First, while global methodologies for carbon credentialing exist under platforms such as the Verified Carbon Standard (VCS) and the Gold Standard, their adaptation to Indonesia's SRN-PPI requirements remains unexplored (Kuncoro et al., 2025). Each carbon-credit protocol requires validation by an accredited Validation and Verification Body/*Lembaga Validasi dan Verifikasi* (LVV) and must comply with national Measurement, Reporting, and Verification (MRV) guidelines that differ substantially from international frameworks. The procedural path for urban-mining projects to progress from conception through validation, registration in the SRN-PPI, issuance of SPE-GRK, and final trading on IDX Carbon has not been systematically documented or tested.

Second, empirical quantification of carbon savings from recycling e-waste gold specific to the Indonesian operational context is lacking. Existing LCA studies mostly reflect energy mixes and technology configurations characteristic of economies with high renewable-energy penetration. Indonesia's electricity grid remains dominated by coal and natural gas, resulting in higher carbon intensity for electricity consumption (Hardiansyah, et al. 2024). Accurate baseline-emission calculations for primary gold production in Indonesia, considering local mining practices, ore characteristics, and energy sources, are necessary to build credible carbon-savings claims. Detailed emissions data from Indonesian e-waste recycling facilities operating on a commercial scale are scarce, with most available information coming from laboratory studies or operations in other countries (Budijono et al., 2021; Raharjo & Utomo, 2021).

Third, mechanisms for integrating carbon credits generated through urban mining with the global bullion-bank ecosystem and precious-metals markets remain underdeveloped. Bullion banks and institutional investors increasingly demand assurances that gold products meet Environmental, Social, and Governance (ESG) criteria, creating market opportunities for green gold or low-carbon gold products (Valcambi SA, n.d.; VP Bank & Chartered Investment, 2022). Establishing a traceability system linking physical gold products to carbon-credit certificates requires coordination between recyclers, verification bodies, carbon registries, and bullion dealers (Lavrador et al., 2025). The absence of a standard protocol for Indonesia-specific green gold certification limits the ability of urban miners to capture price premiums that may be available in sustainability-conscious markets (Fatimah et al., 2024). A conceptual framework integrating the entire system from e-waste collection to global market access through Indonesia's carbon-credit infrastructure is shown in Figure 1.

As shown in Figure 1, this study was designed to respond to a set of unresolved gaps in the existing literature on urban mining, carbon markets, and sustainable precious metal supply chains. Although prior studies have independently examined the environmental benefits of gold recovery from electronic waste using life cycle assessment, the design of carbon credit mechanisms under international standards, and ESG oriented developments in the global bullion market, no study to date has systematically integrated these three domains into a single operational framework tailored to a national regulatory context, particularly that of Indonesia. Existing life cycle assessment studies largely rely on energy mixes and institutional settings of developed economies, leaving the carbon saving potential of urban gold mining under Indonesia's coal dominated electricity grid empirically underexplored. Likewise, international carbon credit methodologies such as Verra Verified Carbon Standard (VCS) and the Gold Standard have not been analytically adapted to

Indonesia's SRN-PPI system for material recovery projects, resulting in a methodological and procedural vacuum for urban mining initiatives seeking formal carbon accreditation. Moreover, the linkage between carbon credits generated from recycled gold and their monetization through both domestic carbon markets, including IDX Carbon, and the global bullion banking ecosystem remains conceptually fragmented and operationally undefined.

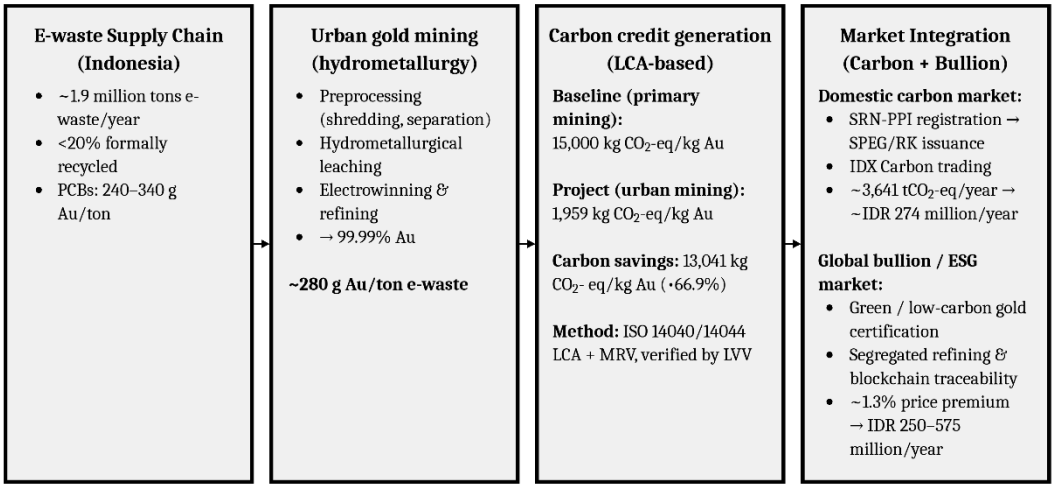

Fig. 1. Conceptual framework showing the interconnections between the electronic waste supply chain, the urban gold mining process, carbon credit generation through Indonesia's SRN-PPI system, the domestic carbon market (IDX Carbon), and global bullion banking integration

Against this backdrop, the novelty of this research lies in its integrated and context specific approach. First, it develops an Indonesia adapted life cycle assessment framework that quantifies carbon savings from substituting primary mined gold with recycled gold recovered from electronic waste under local energy, technological, and logistical conditions. Second, it proposes a hybrid carbon credit protocol that bridges internationally recognized standards, namely Verra VCS and the Gold Standard, with Indonesia's SRN-PPI registration and measurement, reporting, and verification requirements, offering the first detailed procedural roadmap for accrediting urban gold mining projects within the national carbon market infrastructure. Third, the study advances the literature by conceptualizing and operationalizing a mechanism that links carbon credits from urban mining to both the domestic carbon exchange and ESG driven bullion banking systems, including traceability and certification pathways for green gold. Finally, by incorporating a comprehensive economic feasibility analysis, the study quantifies how carbon credit revenues and green gold price premiums jointly enhance project viability, an aspect that remains largely absent from prior environmental or policy oriented studies.

The significance of this research is both theoretical and practical. From a theoretical perspective, it extends circular economy and carbon finance scholarship by demonstrating how emission reductions from material recovery can be structurally embedded within carbon market and commodity finance systems, rather than treated as isolated environmental externalities. From a practical perspective, the findings provide actionable guidance for policy makers, recycling industry operators, and financial institutions by translating sustainability objectives into implementable regulatory, financial, and market mechanisms. By positioning urban gold mining as a credible source of emission reductions and ESG compliant bullion products, this study supports Indonesia's climate mitigation agenda while offering a replicable model for other emerging economies facing similar challenges related to electronic waste accumulation, carbon market development, and sustainable resource governance.

1.1 Circular economy, carbon mitigation, and resource recovery

A theoretical framework linking circular-economy principles with carbon-emission reduction provides a conceptual foundation for addressing this gap. Empirical evidence from 29 European countries shows that circular-economy interventions produce synergistic effects with carbon-mitigation efforts, with minimal offset behavior (Hailemariam & Erdiaw-Kwasie, 2023; Wang et al., 2024). Extending these principles to the precious metals sector requires adaptation to the sector's specific characteristics, including high material value, strict purity requirements, and the existence of an established global bullion market with its own certification and traceability standards.

The regulatory landscape for carbon-credit mechanisms in resource-dependent sectors is evolving rapidly, with an emerging framework for integrating environmental costs into economic decision-making (Mirzehi & Moradi Afrapoli, 2024). Carbon-pricing mechanisms, whether implemented through carbon taxes or emissions-trading systems, generate government revenues that can be allocated toward expanding renewable-energy capacity (Riyono et al., 2025). More fundamentally, the mining sector's shift toward integrating renewable energy and lowering its carbon footprint hinges on the presence of financial instruments that can translate emission reductions into monetary value (Enemuo & Ogunmodimu, 2025). Indonesia's carbon-pricing framework combines sectoral applications covering energy, waste management, and industrial processes, setting a precedent for expanding coverage to urban-mining activities (Sudjonno et al., 2024).

1.2 Asian experience with carbon–circular economy linkages

Comparable work in Asia has linked circular material use with carbon mitigation, although it has generally stopped short of designing a project-level crediting protocol for recovered precious metals. Liu et al. (2018) quantified greenhouse-gas reduction pathways in China's plastic-recycling industries under circular-economy development. Herrador et al. (2022) compared how Japan and South Korea connect circular-economy policy with zero-carbon strategies, while Sugimura et al. (2023) examined the climate implications of increasing secondary raw-material use in Japan's copper industry and compared this option with carbon-credit purchasing. These studies provide a regional basis for connecting material recovery and carbon economics, but they do not establish the Indonesia-specific registry and bullion-market pathway developed in this study

1.3 ESG requirements and responsible bullion markets

Responsible-gold initiatives add a market layer to this carbon–circular economy linkage. Valcambi SA (n.d.) emphasizes traceable sourcing for its Green Gold offering, VP Bank (2022) documents an investment product built around responsibly sourced gold, and Lavrador (2025) identifies sourcing and refining transparency as central considerations for responsible gold investment. In this study, these market practices provide the basis for treating traceability and ESG-oriented product qualification as complementary to, rather than substitutes for, carbon-credit certification.

2. Methods

2.1 Research type and approach

This study adopts a qualitative exploratory design using policy design and comparative regulatory analysis to develop an operational framework aligned with Indonesian regulations, rather than to test laboratory based hypotheses. Policy design is employed to examine existing rules, identify implementation gaps, and formulate feasible institutional solutions (Puluhulawa & Harun, 2024; Sunanda et al., 2025). while comparative regulatory

analysis contrasts international carbon credit methodologies under Verra and the Gold Standard with Indonesia's SRN-PPI requirements to determine an appropriate adaptation framework (Sudjonno, 2024; Kuncoro et al., 2025; Sudjonno et al., 2024).

As a quantitative foundation, the study applies life cycle assessment following ISO 14040 and ISO 14044 standards to quantify environmental impacts across the cradle to gate system boundary, from electronic waste collection to refined gold production (Kadivar et al., 2023; Norgate & Haque, 2012). This approach enables systematic measurement of energy use, material inputs, and emissions, and supports scenario based policy evaluation when integrated with system dynamics modeling (He et al., 2023; Li et al., 2019).

2.2 Data sources

Primary data were derived from Indonesian regulatory documents governing the domestic carbon market, including Presidential Regulation No. 98 of 2021, KLHK technical guidelines for SRN-PPI project registration and verification, and Financial Services Authority regulations on SPE GRK trading on IDX Carbon (Sudjonno, 2024; Sudjonno et al., 2024; Sunanda et al., 2025). International methodological references were obtained from Verra and the Gold Standard, specifically the AMS III BA methodology for material recovery from solid waste, selected for its suitability for small and medium scale urban mining projects (Baskaran et al., 2025). Data on electronic waste conditions in Indonesia were sourced from Ministry of Environment and Forestry/ Kementerian *Lingkungan Hidup dan Kehutanan* (KLHK) and USASCP reports, while regional comparisons relied on the Global E waste Monitor published by United Nations Institute for Training and Research (UNITAR) (Firmansyah et al., 2025; USASCP, 2024).

Secondary data consisted of peer reviewed literature indexed in Scopus and Web of Science. Emission baselines for primary gold mining were drawn from LCA studies by Kadivar et al. (2023), Norgate & Haque (2012), and Aurubis (2024), while emissions from gold recovery from electronic waste were based on Li et al. (2019) and He et al. (2023). Indonesian specific LCA data from Hardiansyah et al. (2024) were used to adjust emission estimates to the domestic coal dominated energy mix.

2.3 Data collection techniques

Data collection was conducted through a systematic document review with a structured search and selection protocol. For academic literature, searches were conducted in the Scopus database using a combination of Boolean keywords: ("urban mining" OR "e-waste recycling" OR "electronic waste") AND ("gold recovery" OR "precious metal") AND ("life cycle assessment" OR "carbon footprint" OR "environmental impact") AND ("carbon credit" OR "carbon pricing" OR "emission trading") with publication restrictions from 2012 to 2025 to ensure relevance and recency. Inclusion criteria included Scopus Q1 or Q2-indexed English-language journal articles that provided quantitative data or an adaptable methodological framework. In contrast, exclusion criteria included articles that focused solely on technological aspects without environmental or economic analysis and studies with limited methodological transparency (Soto-Vázquez, 2025).

For Indonesian regulatory documents, collection was carried out through official government portals, including the websites of the Ministry of Environment and Forestry, the Financial Services Authority, and IDX Carbon. The documents collected included legislation, technical guidelines, and standard forms for carbon project registration and reporting. Authenticity verification is carried out by cross-referencing with the State Gazette and the Official Gazette of the Republic of Indonesia. Unstructured interviews with several key stakeholders from the Directorate General of Climate Change Control of the Ministry of Environment and Forestry, and IDX Carbon operators were conducted to clarify the interpretation of regulations and operational procedures. However, this information was used primarily for triangulation and not as a primary data source (Rahmanda et al., 2023).

2.4 Data analysis techniques

Content analysis was applied to regulatory documents using a deductive coding approach based on the theoretical framework of carbon credit mechanisms. The coding process included the extraction of key principles, technical requirements (baseline definitions, additionality demonstrations, monitoring parameters, verification frequency), and administrative procedures (registration, validation, issuance, and trading) from the SRN-PPI and POJK regulations. Each requirement is mapped to the Verra AMS-III.BA methodology structure to identify compliance, gaps, and potential conflicts that require modification (Kuncoro et al., 2025; Puluhulawa & Harun, 2024). Comparative benchmarking was conducted by compiling a comparison matrix of carbon credit protocols between Verra, Gold Standard, and Indonesia's SRN-PPI to assess how the material recovery methodology can be adapted without compromising methodological integrity and international credibility, supplemented by lessons learned from waste management sector carbon credit projects in the global voluntary market (Baskaran & Byun, 2025; J., 2025).

Because the economic model uses a 10-year project horizon, electricity-related project emissions are not intended to remain fixed to one grid emission factor throughout the crediting period. The 2023 grid factor used in the ex-ante calculation is retained as the base-year parameter reported in this study. For subsequent monitoring years, electricity emissions are recalculated using measured annual electricity consumption and the latest official Indonesian grid emission factor applicable to that monitoring year. This approach allows changes in Indonesia’s coal-dominated generation mix to enter the credit calculation through observed annual factors rather than through an assumed decarbonization trajectory.

Life cycle assessment analysis uses an attributional approach in accordance with ISO 14040/14044 with a gate-to-gate boundary, from the receipt of e-waste at the facility to the production of 99.99 percent pure gold. The functional unit is set at 1 kilogram of pure gold produced. Baseline emission data for conventional gold mining were compiled from LCA studies with geological conditions and energy mix comparable to Indonesia (Kadivar et al., 2023; Norgate & Haque, 2012; Hardiansyah, et al. 2024). Project scenario emissions were calculated by integrating specific energy consumption data for hydrometallurgical processes (Li et al., 2019; Zholdasbay et al., 2024) with Indonesia's electricity grid emission factors from the IEA and the Ministry of Energy and Mineral Resources. Carbon savings were calculated as the difference between baseline and project emissions, with sensitivity analysis on recovery efficiency, energy consumption per ton of e-waste, and regional grid emission factor variations (Cespi et al., 2025; Alvarenga, et al. 2022).

Economic feasibility analysis uses discounted cash flow with a 10-year horizon, calculating net present value, internal rate of return, and payback period. Two scenarios were analyzed: revenue from physical gold sales only, and revenue combining gold sales with revenue from carbon credit trading on IDX Carbon at a price range of IDR 50,000-100,000 (USD 2,76 - 5,51) per ton of CO_2-eq. Sensitivity analysis including global gold price variables, energy costs, recovery efficiency, and domestic carbon prices (Budijono et al., 2021; Deng et al., 2022), while the green gold premium estimate refers to premium data for recycled and low-carbon gold from Valcambi and VP Bank (Valcambi SA, n.d.; VP Bank & Chartered Investment, 2022). The overall research methodology framework, which integrates five stages of analysis from literature review to economic feasibility analysis, is presented in Figure 2. As shown in Figure 2, this integrated methodological approach enables multidimensional analysis that addresses all research objectives in a systematic and coherent manner.

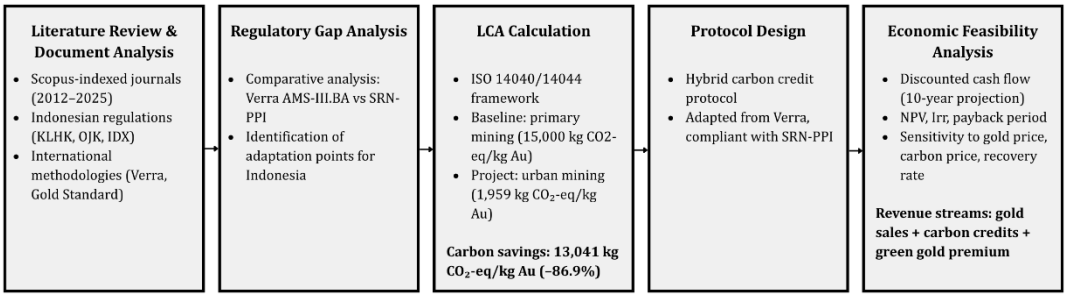

Fig. 2. Flowchart of the research methodology from the literature review to the economic feasibility analysis

3. Results and Discussion

3.1 Quantification of carbon savings from urban gold mining in Indonesia

Life Cycle Assessment calculations for baseline emissions from primary gold production in Indonesia show substantial variation depending on the geological characteristics of the deposit, extraction technology, and operational energy sources. Based on the adaptation of data from (Hardiansyah, et al. 2024), carbon emissions for dore bullion production reach 16,500 kg CO_2-eq per kilogram of gold, with the largest contribution coming from diesel fuel consumption for mining operations and Indonesia's grid electricity, where coal-fired power plants still dominate. This value is slightly higher than the global baseline from Kadivar et al. (2023), which reports 12,200 kg CO_2-eq per kilogram of gold for Nevada operations with more efficient roasting technology, but still within the range reported by Norgate & Haque (2012) of 18,000 kg CO_2-eq per kilogram of gold for low-grade and complex mineral deposits. Data from Aurubis (2024) provides a perspective from an integrated refiner with emissions of 15,400 kg CO_2-eq per kilogram of gold, covering the entire chain from mining to refining with substantial investment in renewable energy.

For the Indonesian context, with an electricity grid carbon intensity of 0.709 kg CO_2-eq per kWh based on 2023 data from the Ministry of Energy and Mineral Resources, this study sets a conservative emissions baseline of 15,000 kg CO_2-eq per kilogram of gold as a weighted average value that reflects the mix of domestic mining technologies. This baseline is in line with the Verra methodology approach, which requires the use of historical data from comparable operations or independently verified literature (Kuncoro et al., 2025). The contribution of each stage to baseline emissions is distributed as follows: mining and comminution 45 percent, leaching and extraction 25 percent, smelting and refining 20 percent, and transportation and support operations 10 percent, a pattern consistent with the findings of Kadivar et al. (2023) and Soto-Vázquez (2025).

Emissions from the urban gold mining project scenario from e-waste were calculated by integrating specific energy consumption data from Li et al. (2019) for hydrometallurgical processes with Indonesia's grid emission factors. The analyzed process chain includes mechanical preprocessing (shredding and separation) with an energy consumption of 250 kWh per ton of e-waste, chemical leaching using aqua regia or thiosulfate 180 kWh per ton, solvent extraction and precipitation 120 kWh per ton, and electrowinning and refining 200 kWh per ton. Assuming an average gold concentration of 280 grams per ton of e-waste based on Xavier et al. (2023) and Phogat et al. (2025), the total energy consumption per kilogram of gold produced reaches 2,679 kWh, equivalent to emissions of 1,899 kg CO_2-eq per kilogram of gold from electricity consumption.

Additional emissions from the use of chemical reagents were calculated using the Ecoinvent v3.9 database for the production of nitric acid, hydrochloric acid, and sodium thiosulfate, resulting in secondary emissions of approximately 45 kg CO_2-eq per kilogram of gold. Emissions from the transportation of e-waste from the collection point to the recycling facility are assumed to be 15 kg CO_2-eq per kilogram of gold based on an average

collection radius of 150 kilometers. Total project emissions for urban gold mining in Indonesia in the baseline scenario are 1,959 kg CO_2-eq per kilogram of gold, with a sensitivity range of 1,650 kg CO_2-eq per kilogram (best case with process optimization and renewable energy use) to 2,450 kg CO_2-eq per kilogram (worst case with conventional processes and a high-intensity grid). These results are in line with He et al. (2023), who reported an environmental footprint of gold recycling of 85-145 kg CO_2-eq per kilogram of gold for the European context with high renewable energy penetration, and Cespi et al. (2025), who found a range of 95-180 kg CO_2-eq per kilogram for the secondary supply chain of precious metals.

Carbon savings are calculated as the difference between baseline emissions and project emissions, resulting in an average value of 13,041 kg CO_2-eq per kilogram of gold, or a reduction rate of 86.9 percent. Sensitivity analysis shows that carbon savings range from 12,550 kg CO_2-eq per kilogram of gold in a conservative scenario (low baseline and high project emissions) to 16,350 kg CO_2-eq per kilogram of gold in an optimistic scenario (high baseline and low project emissions). The variable that most influences the amount of carbon savings is the carbon intensity of the electricity grid used for the recycling process, with every 0.1 kg CO_2-eq per kWh decrease in the grid emission factor resulting in additional savings of 268 kg CO_2-eq per kilogram of gold. These findings underscore the importance of transitioning to renewable energy in urban mining operations, as recommended by Enemuo & Ogunmodimu (2025) for the mining sector in general. A detailed breakdown of emissions by process stage for both baseline and project scenarios is presented in Table 1, which demonstrates that the most significant emission reductions occur in the mining, comminution, and high-temperature processing stages that are eliminated in the urban mining pathway.

Table 1. Comparative life cycle assessment: Breakdown of emissions by process stage for baseline (primary mining) and project (urban mining) scenarios

Process Stage	Baseline Emissions (kg CO_2-eq/kg Au)	Project Emissions (kg CO_2-eq/kg Au)	Reduction (%)
Mining & comminution (ore extraction, crushing, grinding)	6,750	177	97.4
Leaching & extraction (chemical processing)	3,750	128	96.6
Smelting & refining (high-temperature processing)	3,000	142	95.3
Solvent extraction & precipitation	—	85	—
Transportation & support operations	1,500	1,427	4.9
Total	15,000	1,959	86.9

Note: Authors' calculations based on the LCA sources and assumptions cited in Section 4.1.

As shown in Table 1, the urban mining pathway achieves emission reductions exceeding 95% in the ore extraction and thermal processing stages. In comparison, transportation and support operations show more modest decreases (4.9%) due to the distributed nature of e-waste collection and the energy requirements of chemical reagent production.

Figure 3 compares the carbon footprint of this study with previously published LCA studies for both primary mining and urban mining pathways, demonstrating that the emission profile of urban mining in Indonesia, while higher than studies conducted in regions with renewable-heavy electricity grids, still achieves substantial reductions relative to all primary mining scenarios.

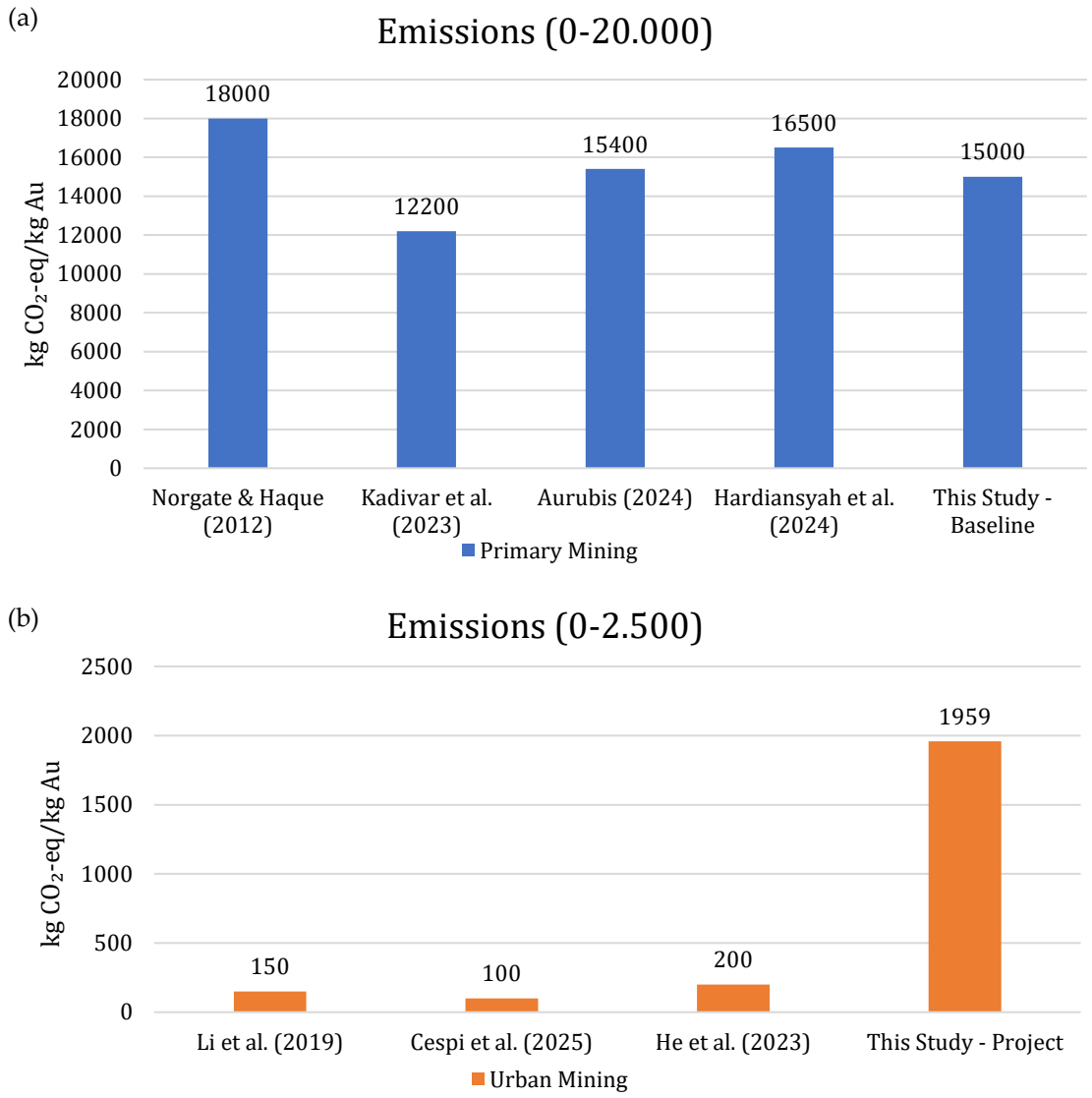

Fig. 3. Comparison charts of carbon footprint (a) primary mining, (b) urban mining.

The higher project emissions observed in this study (1,959 kg CO_2-eq/kg Au) compared to international urban mining benchmarks (100–200 kg CO_2-eq/kg Au) reflect Indonesia's coal-dominated electricity grid with an emission factor of 0.709 kg CO_2-eq/kWh, underscoring the importance of grid decarbonization for maximizing the climate benefits of urban mining.

3.2 Carbon credit protocol design for urban gold mining in Indonesia

The proposed carbon credit protocol adopts the basic structure of the Verra AMS-III.BA (Recovery and Recycling of Materials from Solid Wastes) methodology, which has proven applicable to small and medium-scale projects in the waste management sector, but is adapted to meet the specific requirements of Indonesia's SRN-PPI and the characteristics of urban gold mining. Key modifications include redefining the project boundary to explicitly cover the stages from e-waste preprocessing to the production of pure gold with a minimum purity of 99.99%, establishing a baseline scenario that reflects domestic gold mining practices, and integrating monitoring parameters that are aligned with the national reporting infrastructure.

The additionality component uses a barrier analysis approach to prove that urban gold mining projects would not be viable without additional revenue from carbon credits. The barriers identified include an investment barrier due to the high capital expenditure required for hydrometallurgical facilities with strict environmental standards compared to informal operations, a technological barrier because low-emission recovery technologies require expertise and equipment that are not yet widely available, and an institutional barrier due to the absence of a clear urban mining regulatory framework, which creates uncertainty for investors. This approach is consistent with carbon project validation practices discussed in the Center for International Forestry Research - International Centre for Research in Agroforestry (CIFOR-ICRAF) cross-sector study.

The baseline scenario is set based on the most plausible alternative principle: without urban mining projects, gold is considered to be supplied from conventional mining with emissions of 15,000 kg CO_2-eq per kilogram of gold, as calculated in sub-section 3.1. The scenario that e-waste will end up in landfills or be processed informally is not used as a baseline to avoid double-counting, in line with Government Regulation No. 101 of 2014, which regulates the prohibition of disposing of hazardous waste, including e-waste, without treatment. This approach differs from the typical Verra methodology, which uses landfill disposal as a baseline, but is more relevant to the Indonesian regulatory context.

Leakage issues were identified from two potential sources. First, activity-shifting leakage, where e-waste collected for the project actually comes from existing formal streams; this is addressed by the obligation to prove that the project's feedstock comes from sources not previously covered by the formal system or from new household collection schemes. To reduce supply risk dominated by fragmented informal actors, this protocol proposes an inclusive aggregator model. Rather than displacing informal collectors, the facility operates as a strategic buyer offering tiered pricing incentives based on PCB quality transparency. This approach transforms potential competitors into a reliable supply network, ensuring the 1,000-ton annual feedstock target is achieved without resorting to predatory pricing competition. Second, market leakage occurs when gold from urban mining shifts demand away from other recycled gold without reducing primary mining. Given that the supply scale of this type of project is still well below 1 percent of global gold supply, this risk is treated as de minimis in accordance with carbon accounting practices.

The monitoring parameters set out in the protocol include the volume of e-waste processed per year with evidence from weight bridges and purchase documents, gold recovery rates with independent laboratory test reports, electricity consumption per ton of e-waste based on utility bills and sub-meters, chemical consumption per ton of e-waste through procurement records, and electricity grid emission factors based on official data from the Ministry of Energy and Mineral Resources or Intergovernmental Panel on Climate Change (IPCC) default values. The monitoring frequency is aligned with the SPE-GRK reporting cycle, which is annual, and is verified by an accredited validation and verification body before the issuance of credits.

The permanence aspect of urban mining is relatively straightforward because emissions reductions occur once during gold production, without the risk of reversal as in forestry or soil carbon projects. The protocol, therefore, does not require a buffer pool or temporary crediting and sets a 10-year crediting period that can be extended, in line with the economic life of hydrometallurgical equipment and the planning horizon of the recycling industry. To maintain transaction scale and cost efficiency, the protocol also requires a minimum capacity of 500 tons of e-waste per year or a minimum production of 140 kilograms of gold per year as a project eligibility threshold. The proposed carbon credit protocol is designed with detailed technical specifications to ensure credibility and compliance with international standards (Verra AMS-III.BA) and Indonesian regulations (SRN-PPI), as summarized in Table 2.

Table 2. Key protocol parameters for proposed urban gold mining carbon credit mechanism

Parameter Category	Specification	Rationale	Reference Standard
Methodology Basis	Hybrid approach: Verra AMS-III.BA adapted to Indonesia's SRN-PPI using the local grid emission factor and the domestic baseline currency	Verra AMS-III.BA provides international credibility; adaptation to SRN-PPI ensures domestic compliance; local parameters represent Indonesian conditions	Verra AMS-III.BA v18.0; SRN-PPI Regulation (KLHK 2021); ISO 14040/14044
Functional Unit	1 kilogram refined gold (99.99% purity) recovered from e-waste; baseline unit is 1 kg primary gold from underground or open-pit mining	Purity standard ensures comparable measurement; ISO 14044 requires functional unit equivalence for LCA comparisons	ISO 14040/14044; Verra Greenhouse Gas (GHG) Protocol; London Bullion Market Association (LBMA) Purity Standards
Baseline Scenario	Weighted average emissions of primary gold mining in Indonesia (16,500 kg CO_2-eq per kg gold) plus 5 percent contingency buffer, resulting in a conservative baseline of 16,000 kg CO_2-eq per kg gold	Indonesia-specific baseline increases accuracy; contingency buffer aligns with Verra uncertainty guidance; supports verification defensibility.	Verra AMS-III.BA Section 2; Hardiansyah et al. 2024; Kadivar et al. 2023; SRN-PPI baseline requirements
Additionality Approach	Barrier analysis: without carbon credit revenue of Rp 274 million per year at Rp 75,000 per tCO_2-eq, project Internal Rate of Return (IRR) is 12.8 percent, which is below the hurdle rate of 15 percent. Carbon credit revenue increases IRR by 2.2 percent, making the project financially viable.	Demonstrates financial additionality; quantifiable IRR gap strengthens justification; aligns with Verra barrier analysis tool.	Verra Additionality Tool v20.0; SRN-PPI Additionality Guidance; EB103 Verra Board Decision
Monitoring Frequency	Monthly data collection covering e-waste input mass, power consumption, and gold recovery rate. Annual consolidation into a monitoring report. Verification every 24 months	Monthly data captures seasonal variations; 24-month verification aligns with SRN-PPI requirements; balances integrity and cost.	SRN-PPI Monitoring Guidance; Verra AMS-III.BA Section 5; KLHK Regulation P.47/2021
Verification Body	Independent LVV accredited by KLHK under SRN-PPI with competencies in LCA, e-waste recycling, Indonesian financial accounting, and international carbon market standards	LVV accreditation ensures independence and credibility; multidisciplinary expertise reduces verification risk; supports government recognition	SRN-PPI Regulation; KLHK LVV Accreditation Standard; Verra VCS v4.4 Verification Requirements
Crediting Period	Initial period 10 years starting from SRN-PPI registration; renewable for additional 7-year periods up to a maximum of 30 years, subject to	Ten-year period matches typical investment recovery expectations; renewal option ensures long-term viability;	Verra Project Description Document (PDD) Template; SRN-PPI Crediting Period Guidelines; Kyoto Protocol and Paris

	additionality reassessment and PDD revision	reassessment maintains environmental integrity.	Agreement precedents; International Finance Corporation (IFC) Investment Horizon Standard
Minimum Scale	Minimum 500 tons of e-waste input per year, producing at least 140 kg of gold annually. Projects below this level must be registered under a PoA. The maximum scale is 5,000 tons per year.	Minimum scale ensures issuance of at least 1800 tCO_2-eq per year to justify verification cost; PoA enables aggregation of small processors; maximum scale prevents market dominance.	Verra PoA Methodology VCS v4.4; SRN-PPI Minimum Thresholds; Indonesia e-waste generation profile
Leakage Treatment	Leakage assessed in three categories: (1) market leakage from displacement of informal processors, mitigated through inclusive value chain participation; (2) spatial leakage from substitution of primary mining, assumed negligible based on a substitution rate of less than 5 percent; (3) induced leakage from energy expansion, mitigated by energy efficiency procurement and renewable energy sourcing, with a target of 20 percent by year three	Comprehensive leakage treatment avoids over-crediting; inclusion of informal processors minimizes risks; low substitution rate aligns with global gold supply characteristics; renewable sourcing is feasible in the Indonesian context.	Verra Leakage Assessment Tool v3.2; IPCC Guidance on Leakage; SRN-PPI Leakage Requirements; Soto-Vázquez et al. 2025

Note: AMS-III.BA requirements are summarized from the UNFCCC methodology. Verra states that new VCS projects must apply VMR0008 v1.0 in conjunction with AMS-III.BA. The Indonesian column describes the protocol proposed in this study and does not imply prior approval by SRN-PPI. Sources: UNFCCC (2025); Verra (2023).

As shown in Table 2, each parameter has been designed taking into account the operational context of projects in Indonesia, proven international methodological standards, and SRN-PPI regulatory requirements. The additionality approach based on barrier analysis shows that without revenue from carbon credits, the project would not be implemented due to its inability to achieve the minimum hurdle rate (15%). In contrast, the leakage barrier is overcome through an inclusive value chain design that involves informal processors. Full protocol details, including project boundary definitions, baseline calculation methodology, monitoring plan template, verification checklist, and a sample Project Design Document (PDD) compatible with SRN-PPI registration requirements, are presented in Figure 4.

3.3 Integration mechanism with domestic carbon markets and global bullion banking

The operational pathway for urban gold mining projects to generate and monetize carbon credits in Indonesia begins with the project development and documentation stage. Operators first prepare a Project Design Document that follows the SRN-PPI format, with main content consisting of a description of activities, justification of additionality, calculation of baseline and project emissions, monitoring plans, and environmental safeguards. This document is then submitted to an accredited validation and verification agency for assessment of methodological feasibility and compliance with project eligibility criteria, through a combination of desk review and field visits.

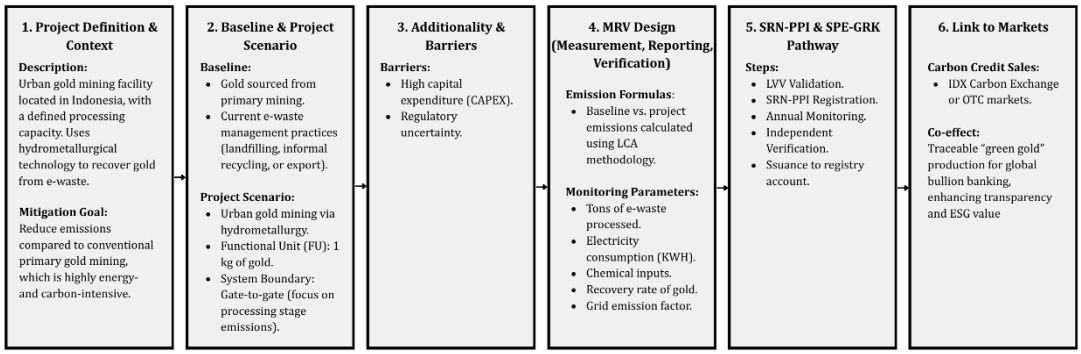

Fig. 4. Stages of the urban gold mining project from e-waste leading to issuance and trading of carbon credits (SPE-GRK)

After validation, project developers submit their registration to the SRN-PPI through the official portal of the Directorate General of Climate Change Control. The registration package includes a validation report, environmental permit, industrial business permit, and proof of legal ownership or management rights to the facility. The authority then conducts an administrative review, which generally takes one to two months, before issuing a Project Registration Number as the official identity in the national system. Only registered projects are eligible to receive a Greenhouse Gas Emission Reduction Certificate (SPE-GRK) and access the domestic carbon market.

During the credit period, developers are required to conduct annual monitoring of key parameters such as the volume of e-waste processed, gold recovery rates, energy and chemical consumption, and actual emissions calculated according to the protocol. This data is summarized in a Project Monitoring Report, which a verification agency then verifies through cross-checking with supporting evidence and sample testing. The verification results are documented in an official report, which serves as the basis for the SRN-PPI administrator to issue SPE-GRK certificates according to the proven reduction in emissions, with one ton of CO_2-eq converted into one certificate unit. For facilities that produce around 280 kilograms of gold per year with savings of 13,041 kg CO_2-eq per kilogram, the annual emission reduction is close to 3,651 tons of CO_2-eq, resulting in an equivalent number of certificates.

Certificates recorded in the project owner's registry account can be traded bilaterally with buyers or through the domestic carbon exchange. The exchange mechanism provides price transparency and standardized transaction procedures, with trading units in lots representing a certain volume of emissions. Early market experience shows a fairly wide price range. However, the average effective price is in the range of tens of thousands of rupiah per ton of CO_2-eq, with cumulative trading volumes still relatively limited. Nevertheless, the combination of physical gold sales and carbon credits is sufficient to improve the financial viability profile of urban mining projects.

In order to connect with the global bullion banking ecosystem, the gold produced needs to be packaged as green gold or low-carbon gold through an additional layer of certification that links physical gold to associated carbon credits. The proposed model mimics the segregated refining practices used by international refiners, where feedstock from e-waste is processed in a separate stream, and each gold bar is assigned a unique serial number linked to a carbon certificate through digital infrastructure such as blockchain. The certificate of origin accompanying each batch lists the quantity and purity of the gold, the source of the e-waste feedstock, the amount of emissions saved per unit, and the verifiable digital transaction identity.

This packaging opens up access to market segments that emphasize ESG performance, including institutional investors and private wealth clients seeking sustainability-oriented investment instruments. Case studies from market players show that low-carbon certified gold products can command a price premium of several percent above the spot price, particularly in the retail segment and among investors with explicit sustainability

mandates. This premium adds to revenue streams beyond carbon credit sales, thereby strengthening the financial incentives for urban mining operators to adopt low-emission technologies and international standard governance. Figure 5 illustrates a comprehensive flowchart of the integration of urban gold mining with two main systems: the Indonesian carbon market (through SRN-PPI and IDX Carbon) and the bullion banking system (through green gold certification and sales to ESG investors).

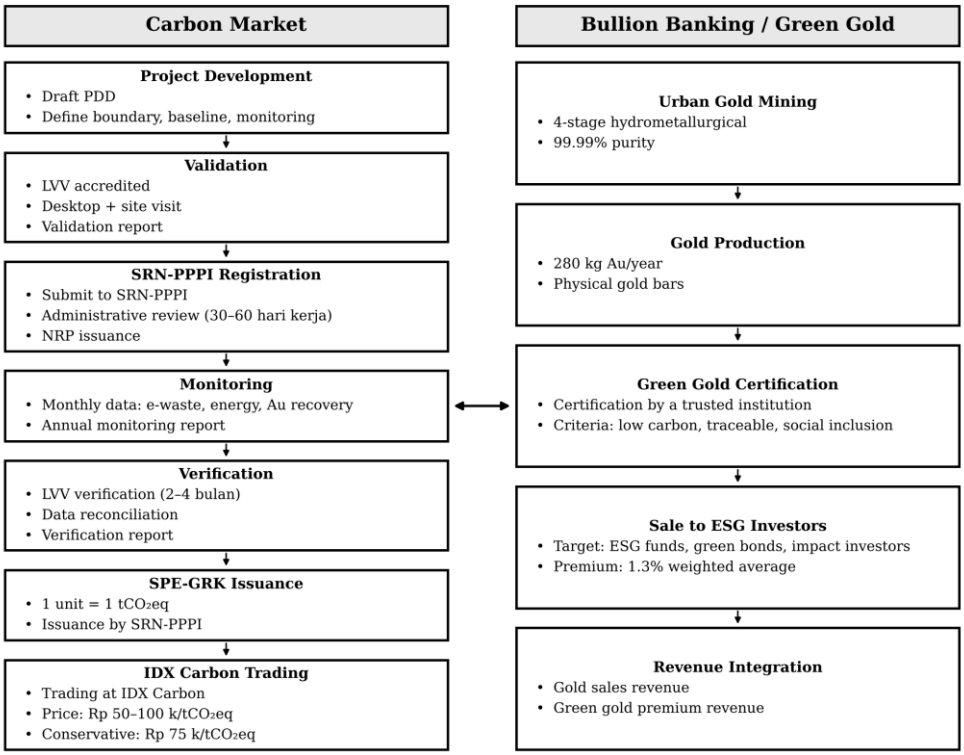

Fig. 5. Flowchart of integration of urban gold mining with the carbon market and bullion banking

As shown in Figure 5, these two streams do not stand alone, but reinforce each other through a feedback loop: revenue from carbon credits is used to upgrade processes and increase recovery rates, which in turn generates more green gold and more premiums; conversely, premiums from green gold support capacity expansion, enabling the processing of more e-waste and the generation of additional carbon credits.

3.4 Economic feasibility analysis and green gold premium estimation

The economic feasibility analysis was conducted using a discounted cash flow model with a 10-year horizon for an urban gold mining project that processes e-waste and produces gold metal as its main product. Based on the latest cost structure calculations, the initial investment (CAPEX) is estimated at IDR 150 billion (USD 8.27 million), which includes the procurement of preprocessing equipment, advanced hydrometallurgical facilities, refining units, and analytical equipment, as well as a comprehensive environmental control system. Annual operating costs (OPEX) are projected at IDR 240 billion (USD 13.23 million), with the largest component allocated to the purchase of e-waste raw materials at market prices, energy costs, chemicals, labor, and regulatory compliance overheads (Budijono et al., 2021).

In the baseline scenario (without carbon credits and without premiums), revenue is projected to come solely from gold sales. Assuming a conservative gold price, annual revenue is estimated at Rp 285.7 billion. With OPEX expenses of Rp 240 billion, the project records an Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA) margin of 16.0 percent. Using a discount rate of 12 percent, the net present value (NPV) of the project reaches IDR 108 billion (USD 5.95 million), with an Internal Rate of Return (IRR)

of 28.5 percent and a payback period of 3.3 years. These indicators show that even though the margin is not very wide due to high raw material costs, the project is still financially feasible (Deng et al., 2022; Mirzehi & Moradi Afrapoli, 2024). Critically, this baseline analysis confirms that the project's financial sustainability rests entirely on the core economics of gold recovery itself. Revenue generated from carbon credits and green gold premiums functions as a value enhancement mechanism rather than a prerequisite for project survival, effectively insulating the project's fundamental viability from the market volatility currently affecting emerging carbon markets.

The second scenario takes into account additional revenue from carbon credits. Assuming a carbon price of IDR 75,000 (USD 4.13) per ton of CO_2-eq, this scenario provides a slight increase in cash flow. Total annual revenue increases slightly to IDR 286.0 billion (USD 15.77 million). Although its contribution to the top line appears small, operational efficiency increases the EBITDA margin to 16.1 percent. In terms of valuation, this scenario raises the NPV to IDR 109.5 billion (USD 6.04 million) (up about 1.4% from the baseline), with an IRR of 28.8 percent and a payback period shortened to 3.2 years (Riyono et al., 2025). This confirms that carbon credits serve as a positive complementary incentive.

The green gold premium estimate is then integrated into the third scenario (combined scenario). Referring to global market practices where certified green gold is priced higher (Valcambi SA, n.d.; VP Bank & Chartered Investment, 2022), this study applies a weighted average premium assumption of around 1.3 percent. In this combined scenario, total annual revenue increases to IDR 289.7 billion (USD 15.97 million). This increase in revenue has a significant impact on profitability, pushing the EBITDA margin to 17.2 percent. The project valuation surges with an NPV of IDR 130 billion (USD 7.17 million) (up 20.4% compared to the baseline), an IRR increasing to 31.2 percent, and a payback period shortening to 3.0 years (Lavrador et al., 2025; Wang et al., 2024).

Overall, the combined scenario integrating gold sales, carbon credits, and green gold premiums offers the most robust financial performance. The substantial increase in NPV in the third scenario confirms that environmental certification and positioning the product as "green gold" not only impacts sustainability credentials but also drives tangible economic value for urban gold mining projects. A summary of the key financial indicators for the three scenarios is presented in detail in Table 3. Although the indicators in Table 3 show positive financial feasibility under the base case assumption, the actual project valuation is highly influenced by external market price dynamics. Therefore, a sensitivity analysis was conducted to test the resilience of the project's NPV to carbon price fluctuations and various levels of green gold premium. The following figure illustrates how changes in carbon credit prices (ranging from IDR 50,000 to IDR 300,000 (USD 2.76 to USD 16.54) per ton of CO_2-eq) interact with variations in the green gold premium (ranging from 0% to 3%) in affecting the project's Net Present Value (NPV).

Sensitivity results indicate that a green gold premium lifts project value more strongly than a carbon price increase on its own. Even at the lowest carbon price assumption (Rp 50,000 per tCO_2-eq), applying a 3% premium raises NPV from IDR 107 billion to IDR 155 billion (USD 5.90 million to USD 8.54 million), showing that premium-driven pricing is the main lever for value creation. Carbon price increases along the horizontal axis still contribute positively and predictably, but the magnitude of uplift remains smaller than the premium effect. Operational stress testing also suggests the facility remains cash-flow positive under “grade dilution,” where feedstock quality falls to 100 g/ton. By adjusting chemical reagent dosing ratios, the hydrometallurgical cost structure can flex to absorb feedstock variability and preserve operating margins.

Table 3. Comparative financial metrics for an urban gold mining project under three scenarios

Financial Metric	Baseline (Gold Sales Only)	With Carbon Credit (IDR 75,000 (USD 4.13) per tCO_2-eq)	Combined Scenario (IDR 75,000 (USD 4.13) per tCO_2-eq + 1.3% Premium)
Initial CAPEX	IDR 150 billion (USD 8.27 million)	IDR 150 billion (USD 8.27 million)	IDR 150 billion (USD 8.27 million)

Annual OPEX	IDR 240 billion (USD 13.23 million)	IDR 240 billion (USD 13.23 million)	IDR 240 billion (USD 13.23 million)
Annual Revenue	IDR 285.7 billion (USD 15.75 million)	IDR 286.0 billion (15.77 million)	IDR 289.7 billion (USD 15.97 million)
EBITDA Margin	16.0%	16.1%	17.2%
NPV (10 years, 12% discount rate)	IDR 108 billion (USD 5.95 million)	IDR 109.5 billion (USD 6.04 million) (+1.4%)	IDR 130 billion (USD 7.17 million) (+20.4%)
IRR	28.5%	28.8%	31.2%
Payback Period	3.3 years	3.2 years	3.0 years

Note: Authors' discounted cash-flow calculations using the assumptions described in Section 4.4.

The relative size of these effects also changes the practical order of priority for project developers. Under the assumptions reported in Table 3, carbon-credit revenue increases NPV by 1.4%, whereas the combined scenario that includes the green-gold premium increases NPV by 20.4% relative to the baseline. The model therefore indicates that ESG-compliant bullion-market access is the stronger value-capture mechanism, while carbon-credit registration provides a complementary revenue and environmental-verification pathway. For operators, the immediate commercial priority is consequently to establish auditable feedstock traceability, chain-of-custody controls, segregated processing, and credible product certification required for sustainability-oriented bullion markets, while pursuing carbon-credit registration in parallel.

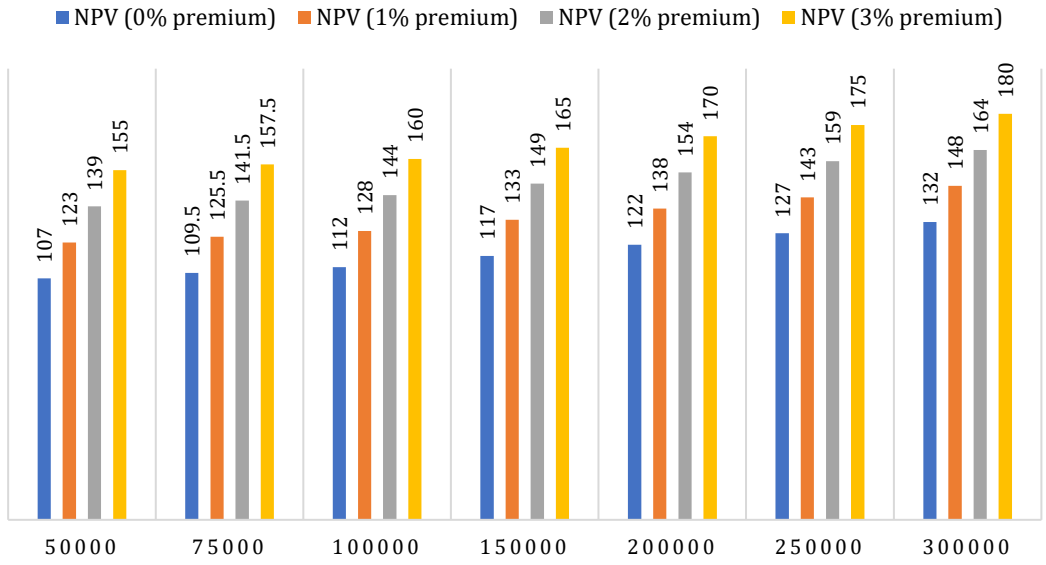

Fig. 6. Bar chart showing NPV values increasing with both carbon price and premium percentage. The X-axis shows carbon prices from 50,000 to 300,000. Bars represent 0%, 1%, 2%, and 3% premiums

4. Conclusions

This study demonstrates that integrating carbon credit mechanisms into gold recovery from electronic waste in Indonesia is technically feasible, economically viable, and regulatorily compatible. Life Cycle Assessment results indicate carbon savings of 13,041 kg CO_2 eq per kilogram of gold, representing an 86.9 percent reduction compared to primary gold production. The proposed carbon credit protocol successfully adapts the Verra AMS III BA methodology to Indonesia's SRN PPI framework and clarifies the full operational pathway from project development to the issuance of greenhouse gas emission reduction certificates, confirming the readiness of Indonesia's regulatory infrastructure to accommodate urban mining projects.

Economic analysis shows that a facility processing 1,000 tons of electronic waste annually achieves a positive net present value of IDR 108 billion (USD 5.95 million)without carbon credit revenue, while the inclusion of green gold premiums increases the NPV to IDR 130 billion (USD 7.17 million), or 20.4 percent higher. Integration with ESG oriented bullion banking systems therefore represents the primary driver of value creation, complemented by carbon credit revenue. These findings position urban gold mining as a strategic instrument for advancing Indonesia's circular economy, climate mitigation objectives, and sustainable finance agenda.

The findings imply distinct implementation roles for Indonesian stakeholders. The national environmental authority and SRN-PPI administrator should provide a clear methodological pathway for verified material-recovery projects, while local governments should strengthen formal e-waste collection and aggregation without excluding informal collectors. Recycling operators should maintain auditable mass-balance, energy-use, assay, and chain-of-custody records that support both carbon verification and green-gold claims. Validation and verification bodies should ensure competence in e-waste processing and life-cycle carbon accounting, and IDX Carbon can provide the transaction pathway once eligible certificates are issued. Refiners, bullion-market intermediaries, and financial institutions should prioritize traceability, segregated processing, and ESG product qualification because the study's financial results identify the green-gold premium as the stronger value driver.

This study is subject to several limitations. The Life Cycle Assessment relies on secondary data and assumes average process efficiencies and grid emission factors, which may differ across regions and facility designs. Carbon price and green gold premium estimates are based on current market observations and may change as domestic and global markets mature. In addition, the analysis does not include social impact quantification or behavioral responses from informal recycling actors.

Future research should incorporate primary operational data from commercial scale facilities, evaluate dynamic electricity decarbonization scenarios, and examine social and institutional impacts of formalizing urban mining supply chains. Further studies may also explore blockchain based traceability systems in greater depth and assess the scalability of this framework to other critical metals and emerging economies.

Acknowledgement

The authors would like to thank the E-waste Management Division of the Ministry of Environment and Forestry for providing access to regulatory documents and market data, and colleagues who provided comments on earlier drafts of this manuscript.

Author Contribution

Conceptualization, B.N. and A.F.; Methodology, B.N. and A.F.; Software, B.N.; Validation, B.N. and A.F.; Formal analysis, B.N.; Investigation, B.N.; Resources, B.N.; Data Curation, B.N.; Writing - Original Draft, B.N.; Writing - Review & Editing, B.N. and A.F.; Visualization, B.N.; Supervision, A.F.; Project administration, A.F.

Funding

PT Pegadaian funded this research and fully covered the article processing charge (APC) as part of the joint Call for Papers program.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

The study relies on secondary data from publicly available reports and academic literature. No new datasets were generated or analyzed in this study.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used DeepL to assist in translating parts of the manuscript, Grammarly to assist in improving grammar, clarity, and academic tone, and Perplexity AI to assist in reviewing structure and consistency. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Open Access

©2026. The authors. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original authors and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

References

Aurubis. (2024). *Life cycle assessment of Aurubis silver and gold*. https://www.aurubis.com/en/responsibility/reporting-kpis-and-esg-ratings

Baskaran, D., & Byun, H.-S. (2025). Future-proofing CO2 mitigation towards a circular economy: A systematic review on process integration and advanced tools. *Environmental Science and Ecotechnology, 26*, 100587. https://doi.org/10.1016/j.ese.2025.100587

Budijono, Z., Ronyastra, I. M., & Soegiharto, S. (2021). Studi kelayakan pendirian industri ekstraksi emas dari e-waste di Surabaya. *KELUWIH: Jurnal Sains dan Teknologi, 2*(1). https://doi.org/10.24123/saintek.v2i1.4050

Cespi, D., Ciacci, L., Chiarini, A., Trova, E., Acciai, C., Ciabatti, I., Tirinnanzi, M., & Passarini, F. (2025). LCA of precious metals recovery: Modelling the secondary supply of gold, silver, platinum, palladium and rhodium from an integrated refining plant. *Cleaner Environmental Systems, 19*, 100310. https://doi.org/10.1016/j.cesys.2025.100310

Deng, S., Xiao, Z., Zhang, W., Noble, A., Das, S., Yih, Y., & Sutherland, J. W. (2022). Economic analysis of precious metal recovery from electronic waste through gas-assisted microflow extraction. *Resources, Conservation and Recycling, 190*, 106810. https://doi.org/10.1016/j.resconrec.2022.106810

Enemuo, M., & Ogunmodimu, O. (2025). Transitioning the mining sector: A review of renewable energy integration and carbon footprint reduction strategies. *Applied Energy, 384*, 125484. https://doi.org/10.1016/j.apenergy.2025.125484

Fatimah, Y. A., Govindan, K., Sasongko, N. A., & Hasibuan, Z. A. (2024). The critical success factors for sustainable resource management in circular economy: Assessment of urban mining maturity level. *Journal of Cleaner Production, 469*, 143084. https://doi.org/10.1016/j.jclepro.2024.143084

Firmansyah, M. L., Rizki, I. N., & Ullah, N. (2025). Recent advances in urban mining technology: A focus on electronic waste recycling potential in Indonesia. *Cleaner Waste Systems, 10*, 100239. https://doi.org/10.1016/j.clwas.2025.100239

Hailemariam, A., & Erdiaw-Kwasie, M. O. (2023). Towards a circular economy: Implications for emission reduction and environmental sustainability. *Business Strategy and the Environment, 32*(4), 1951–1965. https://doi.org/10.1002/bse.3229

Hannany, Z., & Priambodo, D. (2025, July 16). Carbon trading plunges 98.5% in June 2025, IDX chief responds. *IDN Financials*. https://www.idnfinancials.com/news/55927/carbon-trading-plunges-98-5-in-june-2025-idx-chief-responds

Hardiansyah, R., Yuniarto, A., Habib, S., & Rosalina Sari, E. (2024). Kajian life cycle assessment proses produksi dore bullion pertambangan emas di Jawa Barat. *Jurnal Serambi Engineering, 9*(3), 9898–9906. https://jse.serambimekkah.id/index.php/jse/article/view/330

He, Y., Hosseinzadeh-Bandbafha, H., Kiehbadroudinezhad, M., Peng, W., Tabatabaei, M., & Aghbashlo, M. (2023). Environmental footprint analysis of gold recycling from electronic waste: A comparative life cycle analysis. *Journal of Cleaner Production, 432*, 139675. https://doi.org/10.1016/j.jclepro.2023.139675

Herrador, M., de Jong, W., Nasu, K., & Granrath, L. (2022). Circular economy and zero-carbon strategies between Japan and South Korea: A comparative study. *Science of The Total Environment, 820*, 153274. https://doi.org/10.1016/j.scitotenv.2022.153274

Kadivar, S., Akbari, H., & Vahidi, E. (2023). Assessing the environmental impact of gold production from double refractory ore in a large-scale facility. *Science of The Total Environment, 905*, 167841. https://doi.org/10.1016/j.scitotenv.2023.167841

Kandulu, J., Wheeler, S., & Pham, T. T. (2025). *Carbon pricing: Approaches, lessons and recommendations for blue carbon in Vietnam*. Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF). https://doi.org/10.17528/cifor-icraf/009371

Kuncoro, A. H., Dwijatmiko, A., Noer'aida, Nurliyanti, V., Sugiyono, A., Widhiatmaka, Subandriya, A., Hesty, N. W., Ali Nandar, C. S., Febijanto, I., Wahid, L. O. M. A., & Butarbutar, P. (2025). Mapping the landscape of carbon trading & carbon offset research: A global and Indonesian perspective. *AIMS Energy, 13*(1), 86–124. https://doi.org/10.3934/energy.2025004

Lavrador, D., Döbeli, S., & Brunner, K. (2025). *Responsible gold investments: SSF spotlight*. Swiss Sustainable Finance. https://www.sustainablefinance.ch/api/rm/CRAG33WK9GXZ573/ssf-pub-responsible-gold-investment-final-2.pdf

Li, Z., Diaz, L. A., Yang, Z., Jin, H., Lister, T. E., Vahidi, E., & Zhao, F. (2019). Comparative life cycle analysis for value recovery of precious metals and rare earth elements from electronic waste. *Resources, Conservation and Recycling, 149*, 20–30. https://doi.org/10.1016/j.resconrec.2019.05.025

Liu, Z., Adams, M., Cote, R. P., Chen, Q., Wu, R., Wen, Z., Liu, W., & Dong, L. (2018). How does circular economy respond to greenhouse gas emissions reduction: An analysis of Chinese plastic recycling industries. *Renewable and Sustainable Energy Reviews, 91*, 1162–1169. https://doi.org/10.1016/j.rser.2018.04.038

Mirzehi, M., & Moradi Afrapoli, A. (2024). A novel framework for integrating environmental costs and carbon pricing in open-pit mine plans: Towards sustainable and green mining. *Journal of Cleaner Production, 468*, 143059. https://doi.org/10.1016/j.jclepro.2024.143059

Norgate, T., & Haque, N. (2012). Using life cycle assessment to evaluate some environmental impacts of gold production. *Journal of Cleaner Production, 29–30*, 53–63. https://doi.org/10.1016/j.jclepro.2012.01.042

Phogat, P., Kumar, S., & Wan, M. (2025). A scientometrics study of advancing sustainable metal recovery from e-waste: Processes, challenges, and future directions. *RSC Sustainability, 3*(6), 2434–2454. https://doi.org/10.1039/D5SU00049A

Puluhulawa, F., & Harun, A. A. (2024). Enabling circular economy: Towards sustainable electronic waste management regulation. *Jambura Law Review, 6*(1), 33–65. https://doi.org/10.33756/jlr.v6i1.24024

Raharjo, S., & Utomo, A. H. (2021). Comparative study of electronic waste management in developed countries and Indonesia. *Andalasian International Journal of Applied Science, Engineering and Technology, 1*(1), 21–32. https://doi.org/10.25077/aijaset.v1i1.4

Rahmanda, B., Njatrijani, R., & Fadillah, R. (2023). Environmental policy in managing e-waste recycling: Promoting a clean environment in public policy. *International Journal of Sustainable Development and Planning, 18*(1), 121–126. https://doi.org/10.18280/ijsdp.180112

Riyono, K. M., Stanley, N., & Widianingsih, L. P. (2025). Carbon pricing as a revenue stream for greener future. *Jurnal Akuntansi Kontemporer, 17*(2), 108–122. https://doi.org/10.33508/jako.v17i2.7247

Soto-Vázquez, R. (2025). Life-cycle assessment in mining and mineral processing: A bibliometric overview. *Green and Smart Mining Engineering, 2*(1), 73–83. https://doi.org/10.1016/j.gsme.2025.02.001

Sudjonno, Y., PwC, Suarga, R., & Indonesia Carbon Trade Association. (2024). *Indonesia carbon market white paper*. PwC Indonesia. https://www.pwc.com/id/en/publications/esg/indonesia-carbon-market-white-paper.pdf

Sugimura, Y., Kawasaki, T., & Murakami, S. (2023). Potential for increased use of secondary raw materials in the copper industry as a countermeasure against climate change in Japan. *Sustainable Production and Consumption, 35*, 275–286. https://doi.org/10.1016/j.spc.2022.11.007

Sunanda, W., Setyonegoro, M. I. B., Hadi, S. P., & Sarjiya. (2025). Advancing the carbon pricing framework in Indonesia: A systematic review of policies, challenges, and global lessons. *Results in Engineering, 28*, 107155. https://doi.org/10.1016/j.rineng.2025.107155

USASCP. (2024). *E-waste management in Indonesia: Ministry of Environment and Forestry.* USASCP. https://www.usascp.org/wp-content/uploads/2024/08/7.18-E-Waste-Management-in-Indonesia_Mahanani-Kristianingsih.pdf

Valcambi SA. (n.d.). *Green gold: Traceable & ethical gold by Valcambi*. Retrieved December 5, 2025, from https://valcambi.com/responsibility/green-gold/

VP Bank & Chartered Investment. (2022). *VP Bank media release: Certificate green gold*. https://www.vpbank.com/sites/default/files/assets/downloads/20220920_VP_Bank_media_release_green_gold_EN.pdf

Wang, N., Bai, Y., Guo, Z., Fan, Y., & Meng, F. (2024). *Synergies between the circular economy and carbon emission reduction*. SSRN. https://doi.org/10.2139/ssrn.4713910

Xavier, L. H., Ottoni, M., & Abreu, L. P. P. (2023). A comprehensive review of urban mining and the value recovery from e-waste materials. *Resources, Conservation and Recycling, 190*, 106840. https://doi.org/10.1016/j.resconrec.2022.106840

Zholdasbay, E. E., Argyn, A. A., Dosmukhamedov, N. K., & Kaplan, V. A. (2024). Gold recovery from electronic scrap waste by low-temperature chloridizing roasting. *Non-Ferrous Metals, 56*(1), 22–27. https://doi.org/10.17580/nfm.2024.01.04

Biographies of Authors

Beckham Napitupulu, a Public Sector Accounting student specializing in Information Systems at Politeknik Keuangan Negara STAN, South Tangerang, Banten, Indonesia. He integrates financial expertise with technological proficiency. With a strong academic focus on corporate finance, auditing, and fiscal policy, he excels in data-driven financial analysis and strategic planning. His interdisciplinary skills are demonstrated through active participation in prestigious business case and policy paper competitions. Beyond his analytical pursuits, Beckham is a dynamic contributor to campus life, balancing rigorous academic standards with leadership roles in organizational committees.

- Email: beckham_4131230349@pknstan.ac.id
- ORCID: 0009-0009-9738-7873
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Aidatul Fitriyah, affectionately known as Afriya, is an award-winning researcher and distinguished alumnus of Universitas Airlangga, Surabaya, East Java, Indonesia. With a strong background in English Language and Literature, she has established expertise in interdisciplinary research covering linguistics, media studies, and environmental sustainability. Her impressive academic portfolio includes over 25 published articles and two books chapter. Her notable works range from critical discourse analyses of religious representation in film to the development of zero-waste palm oil biorefineries for Sustainable Aviation Fuel. She experienced as a Journal Manager and International Marketing Specialist at Indonesian Scientific Publication.

- Email: aidatul.fitriyah-2020@fib.unair.ac.id
- ORCID: 0000-0003-0195-372X
- Web of Science ResearcherID: ACQ-1958-2022
- Scopus Author ID: 59419339100
- Homepage: N/A