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## EDITED BY

Chao Wang,  
Capital University of Economics and  
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## REVIEWED BY

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Charles Darwin Foundation, Ecuador  
Gui Jin,  
China University of Geosciences  
Wuhan, China

## \*CORRESPONDENCE

Andrianto Ansari  
✉ andrianto.ansari@mail.ugm.ac.id

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# Integrating cutting-edge technology, nature based solutions, and circular bioeconomy for upland restoration toward regenerative landscapes

Jaka Widada<sup>1</sup>, Subejo<sup>2</sup>, Widiyatno<sup>3</sup>, Najmu Tsaqib Akhda<sup>2</sup>,  
Andi Syahid Muttaqin<sup>4</sup>, Sawitri<sup>3</sup>, Ishadiyanto Salim<sup>2</sup>,  
Fiqri Ardiansyah<sup>3</sup>, Muhammad Chrisna Satriagasa<sup>3</sup>,  
Sunarno A. Rakino<sup>5</sup>, Natalia Permata Sari Br Bangun<sup>5</sup> and  
Andrianto Ansari<sup>6\*</sup>

<sup>1</sup>Department of Agricultural Microbiology, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia, <sup>2</sup>Department of Agricultural Socio-Economics, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia, <sup>3</sup>Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta, Indonesia, <sup>4</sup>Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia, <sup>5</sup>Indonesia Asahan Aluminium (INALUM) Ltd., Asahan, Indonesia, <sup>6</sup>Department of Agronomy, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia

Tropical uplands provide essential ecological functions and socio-economic benefits, but they are rapidly degrading due to deforestation and unsustainable agriculture. This leads directly to severe soil erosion and biodiversity loss. Critically, current restoration efforts are often small-scale, ecologically inefficient, and poorly integrated with local socio-economic needs, resulting in fragmented and ultimately unsustainable outcomes. Conventional reforestation efforts often fall short due to high costs, low seedling survival, and limited community involvement. This perspective presents an integrated framework for upland restoration that combines cutting-edge technology, nature-based solutions, and circular bioeconomy principles. Unmanned aerial vehicles (UAVs) or drones offer a scalable and precise method for distributing seedballs and monitoring ecological progress in challenging terrain, greatly reducing labor and time. Complementary to this, the use of arbuscular mycorrhizal fungi (AMF) improves plant establishment by enhancing nutrient uptake, water absorption, and microbial diversity, particularly in degraded soils. These innovations are unified under a circular bioeconomy model, which promotes the use of biodegradable inputs, local biomass, and species with ecological and economic value. The synergy of these elements results in a modular, adaptive, and community-based system that enhances ecological function while generating rural employment and reducing dependence on external inputs. The model is applicable across diverse restoration contexts and aligns with broader sustainability goals. Through integrating technology, biology, and circular systems thinking, this framework offer adaptive and innovative approaches to restoration for supporting global agendas such as the UN Decade on Ecosystem Restoration and the Sustainable Development Goals.

## KEYWORDS

upland, tropical, restoration, drone, mycorrhiza, circular bioeconomy

# 1 Introduction

Tropical uplands serve as ecological keystones, regulating watershed functions, housing biodiversity hotspots, and sustaining the livelihoods of millions (Lebel and Daniel, 2009; Castillo-Figueroa, 2021). However, these regions are undergoing rapid degradation where unsustainable practices like slash-and-burn agriculture, deforestation, illegal mining, and monoculture plantations have severely undermined soil health, forest cover, and ecosystem services (Mahala, 2019; Nyssen et al., 2009). In Indonesia alone, Millions of hectares of upland forests have been converted or degraded over the last three decades, and this destruction has caused cascading effects like landslides, water shortages, and increased greenhouse gas emissions in regions such as Toba Lake [MoEF (Ministry of Environment and Forestry of Indonesia), UNCCD (United Nations Convention to Combat Desertification), 2015; Saragih and Sunito, 2001]. The degraded condition of these landscapes impairs natural regeneration, posing a major obstacle to national and regional climate and sustainability goals. In response to these challenges, reforestation has become a central strategy in landscape rehabilitation programs (Indrajaya et al., 2022; Stanturf et al., 2024; Gigendhiran et al., 2025). Although reforestation and land rehabilitation programs have been implemented across several areas using conventional restoration methods, their success rates vary considerably. Conventional restoration methods are often characterized by high labor costs, difficult terrain access, low seedling survival, and heavy reliance on synthetic inputs such as fertilizers and plastic seedling containers (Castro et al., 2024; Southworth and Nagendra, 2009). These limitations, combined with a lack of community engagement and post-planting support, often result in reforested areas failing to establish into self-sustaining ecosystems (Kemppinen et al., 2020; Southworth and Nagendra, 2009). As a result, increasing demand for innovative, system-based solutions that enhance the efficiency, ecological integrity, and socio-economic relevance of restoration efforts arises from multiple stakeholders, including governments seeking scalable climate solutions, local communities aiming to restore livelihoods and ecosystem services, and industries pursuing low-carbon and sustainable sourcing strategies.

In light of these persistent constraints, restoration practitioners and researchers are increasingly turning to the integration of cutting-edge technologies, nature-based solutions, and circular economic thinking to overcome operational, ecological, and economic barriers. Emerging technologies such as unmanned aerial vehicles (UAVs)—commonly referred to as drones—offer a promising tool for reforestation, enabling rapid, precise, and low-impact delivery of seeds or seedlings across remote and degraded terrains (Castro et al., 2024, 2023). Unlike traditional planting, drone-based systems can access areas otherwise unreachable by human labor and apply uniform planting patterns that improve spatial coverage and reduce soil disturbance (Castro et al., 2023; Fortes, 2017). At the same time, nature-based solutions—particularly the use of arbuscular mycorrhizal fungi (AMF)—are gaining momentum as critical allies in restoring soil health and plant resilience (Pozo and Azcón-Aguilar, 2007; Morte and Andrino, 2013; Rasmussen and Rasmussen, 2014). AMF, through their symbiotic relationships with plant roots, enhance nutrient

uptake, water absorption, and resistance to environmental stressors (Morte and Andrino, 2013; Teste et al., 2009). Their application during the early stages of reforestation significantly increases the survival rate and performance of seedlings, especially in nutrient-poor and moisture-limited environments typical of degraded uplands (Rasmussen and Rasmussen, 2014; Badano and de Oca, 2022).

In light of these persistent constraints, restoration practitioners and researchers are increasingly turning to the integration of cutting-edge technologies, nature-based solutions, and circular economic thinking to overcome operational, ecological, and economic barriers. The circular bioeconomy provides the systems-thinking foundation that unites these approaches (Tan and Lamers, 2021; Carus and Dammer, 2018). Rather than following a linear input-output model, the circular bioeconomy emphasizes the use of renewable biological resources, waste minimization, and feedback loops that continuously recycle materials and nutrients (Ansari et al., 2023; Holden et al., 2023). In the context of reforestation, this involves using biodegradable seed carriers such as seedballs made from local organic waste, cultivating native microbial inoculants, and promoting plant species that provide multifunctional biomass for energy, compost, or forage. This model supports restoration not only as a short-term ecological intervention but also as a long-term, regenerative, and economically integrated practice. Through combining drone-based precision planting, microbial symbiosis, and circular resource flows, restoration can be redesigned from a fragmented, resource-intensive effort into a regenerative and community-driven system that rebuilds both ecosystems and livelihoods. Revenue from these activities can be reinvested to cover maintenance, training, and equipment renewal, ensuring financial and operational continuity. While classical restoration seeks to return ecosystems to their original pre-disturbance states, our framework prioritizes the recovery of ecological functionality, microbial diversity, and socio-economic resilience in degraded tropical uplands. The integration of drone-assisted seed deployment, arbuscular mycorrhizal fungi inoculation, and circular bioeconomy principles therefore supports a regenerative rehabilitation pathway—one that enhances ecosystem processes and community wellbeing simultaneously. This approach differs from mitigation, which merely offsets degradation impacts, by emphasizing self-sustaining landscape recovery through the coupling of ecological and socio-economic systems.

## 2 The integration of cutting-edge technology, nature-based solutions, and circular bioeconomy

Integrating cutting-edge technology, nature-based solutions, and circular bioeconomy into restoration is not simply a matter of combining tools—it represents a new design philosophy that redefines how ecological recovery is conceptualized and implemented. Each of these domains addresses distinct functional needs within a restoration system, and their integration produces synergies that significantly improve both the efficiency and

resilience of interventions. UAV technology provides spatial precision and scalability, Nature-based solutions strengthens ecological resilience through biological symbiosis, and the circular bioeconomy links both within a regenerative socio-economic cycle. The integration of these elements directly supports essential restoration processes such as mapping, pelleting, route planning, seedling establishment, and monitoring. Drone-based planting, as an application of cutting-edge technology, functions primarily as a spatial delivery and monitoring platform (Castro et al., 2021). Its most strategic advantage lies in its ability to scale reforestation operations rapidly and precisely in terrain that is otherwise inaccessible or logistically constrained (Castro et al., 2023; Robinson et al., 2022). Unlike manual planting, drones enable uniform seed dispersal, reduced labor costs, and minimal site disturbance (Southworth and Nagendra, 2009; Castro et al., 2023; Robinson et al., 2022). Their integration with geospatial mapping and remote sensing technologies also allows for continuous post-planting monitoring, which is essential for adaptive management in restoration projects (Mohan et al., 2021; Stamatopoulos et al., 2024). The ability to overlay planting designs with soil, slope, and vegetation data further enhances restoration planning and evaluation, ensuring that interventions are site-specific and performance-driven (Castro et al., 2021; Robinson et al., 2022; Mohan et al., 2021). Drone systems also facilitate automated route planning to maximize coverage and efficiency, while their payload configurations allow for the targeted pelleting of seeds. In addition, drones provide real-time data to update planting protocols dynamically in response to environmental feedback, improving responsiveness and long-term monitoring. While UAVs offer scalable planting solutions, their operation in remote uplands may be limited by battery charging infrastructure. Solar-based or hybrid field units could help address this constraint. The “precision” of UAV seeding mainly refers to spatial control rather than exact seed placement, as terrain roughness, vegetation cover, and litter can reduce seed–soil contact and establishment.

Nature-based solutions, in contrast, work at the biological interface between plants and their environment (Gafur et al., 2025). The incorporation of arbuscular mycorrhizal fungi (AMF) into planting systems exemplifies the use of ecological processes to support restoration (Pozo and Azcón-Aguilar, 2007; Gafur et al., 2025; Markovchick et al., 2023). AMF inoculation enhances nutrient acquisition and water absorption, particularly in phosphorus-deficient and drought-prone soils common to degraded upland environments (Pozo and Azcón-Aguilar, 2007; Chaudhury et al., 2024; Smith et al., 2011). Strain–host compatibility strongly influences restoration outcomes; for instance, *Glomus intraradices* and *Rhizophagus irregularis* show high adaptability with tropical upland species such as *Calliandra calothyrsus* and *Albizia chinensis* (Chaudhury et al., 2024; Smith et al., 2011; Berta et al., 2002), enhancing nutrient acquisition and early survival. This biological strategy strengthens plant–soil feedbacks, improves root development, and fosters belowground biodiversity (Morte and Andrino, 2013; Chaudhury et al., 2024). With increasing early seedling vigor and survival, AMF inoculation complements the spatial efficiency of drone planting through critical physiological resilience. Importantly, this symbiosis also contributes to long-term soil restoration through the buildup of organic matter and the re-establishment

of microbial networks (Pozo and Azcón-Aguilar, 2007; Morte and Andrino, 2013; Rasmussen and Rasmussen, 2014; Berta et al., 2002). When deployed together, drones ensure that AMF-enriched propagules are distributed precisely where they are needed, bridging ecological and technological domains. Seed establishment is also affected by post-dispersal factors such as predation, desiccation, or limited burial. Improving seedball design with biodegradable coatings or water-retentive materials may enhance protection and germination under such conditions.

What binds these tools into a sustainable system is the application of circular bioeconomy principles. This framework reframes restoration not as a one-way input-output system, but as a regenerative cycle in which resources are reused, waste is minimized, and value is created at multiple stages (D’Amato et al., 2020; Priyadarshini and Abhilash, 2020). Seedballs used in drone deployment, for example, can be made from locally available biodegradable materials such as clay, compost, and charcoal dust—byproducts of agricultural and domestic activities. AMF inoculum, rather than being imported, can be cultivated using local substrates, reducing costs and preserving native microbial ecotypes. Fast-growing, multipurpose species like *Calliandra calothyrsus* Meisn. can be selected not just for ecological function but for economic utility—providing fodder, green manure, and fuelwood after canopy closure (Binayao et al., 2021; de Luna et al., 2020). In doing so, restored landscapes begin to yield functional biomass that supports local needs while maintaining ecological integrity. Moreover, value-added components such as community-based seedball workshops, biofertilizer production, and drone service cooperatives become part of the circular economy, transforming restoration into a livelihood-generating sector.

Together, these three elements form a coherent, self-reinforcing model. Drones serve as precision tools for initial deployment and long-term monitoring; AMF enhances the biological viability and environmental fit of planted species; and the circular bioeconomy ensures that material flows remain local, renewable, and economically beneficial. More than a collection of tools, this integration represents a paradigm in which restoration is viewed not as an ecological repair job, but as a designed system capable of sustaining itself and contributing to broader development goals. The strength of this model lies in its modularity—it can be adapted to different ecological contexts, scaled to match local capacity, and embedded within community-based restoration strategies. Emphasizing the interconnection of technology, biology, and economics allows this approach to reflect the multifaceted realities of actual landscapes. It addresses the demand for solutions that can scale effectively while remaining grounded in local context. Rather than viewing degraded areas solely as ecological losses, it frames them as opportunities for social and economic renewal. The combined use of advanced tools, ecological processes, and circular resource flows creates a practical and forward-oriented framework for achieving both environmental recovery and community resilience. While traditional restoration relies on costly, inefficient manual labor and linear systems in remote terrain, the framework presented here integrates UAV-based automation, microbial symbiosis, and circular bioeconomic resource flows to provide a more adaptive and cost-efficient pathway for ecological recovery.

### 3 The impact of conceptual framework on socio-economic-environment

The integrated restoration framework described herein has the potential to influence not just ecological metrics, but also social structures and economic resilience. Its environmental impact begins with immediate outcomes such as increased seedling survival and more efficient plant establishment, but extends further into long-term improvements in soil quality, water retention, and biodiversity (Castro et al., 2023; Fortes, 2017; Pozo and Azcón-Aguilar, 2007; Morte and Andrino, 2013; Robinson et al., 2022; Priyadarshini and Abhilash, 2020). AMF colonization fosters microbial diversity and carbon storage below ground, while vegetative cover delivers climate regulation and erosion control above ground (Chaudhury et al., 2024; Elahi et al., 2012; Li et al., 2008). Socially, the model contributes to capacity building, skill development, and community participation in environmental management. Restoration becomes not just an ecological task, but a community enterprise. Local involvement in seedball production, AMF cultivation, drone deployment, and monitoring creates new job opportunities and strengthens local ownership over land-use decisions. This is especially valuable in rural and remote areas where employment options are limited and land degradation undermines livelihoods. From an economic perspective, circular resource flows ensure that the benefits of restoration extend beyond the ecological sphere (Carus and Dammer, 2018; Giampietro, 2019). Biomass generated through restoration can be used locally for energy, compost, or fodder (Kumar Sarangi et al., 2023). The reduced need for synthetic fertilizers and imported planting materials lowers input costs for farmers. This closed-loop system reduces vulnerability to market fluctuations and promotes self-sufficiency (Klein et al., 2022). It also supports broader goals such as food security, energy sovereignty, and climate resilience. In combination, the environmental, social, and economic dimensions of this framework reinforce each other in a regenerative feedback loop. Improved ecosystems support livelihoods, engaged communities sustain the landscape, and circular economies reduce the footprint of intervention (Tan and Lamers, 2021; Carus and Dammer, 2018; Muscat et al., 2021). This synergy makes the model highly adaptable across different ecological contexts and scalable from village-level efforts to national programs. It also aligns with multiple global frameworks, including the UN Decade on Ecosystem Restoration and the Sustainable Development Goals (Bandyopadhyay and Maiti, 2022; Abhilash, 2021).

Each factor in the SWOT matrix is supported by evidence from various literature review (Table 1). To address weaknesses and threats, targeted actions such as capacity-building for drone operators, subsidies for renewable energy infrastructure, and ecological risk assessment protocols are recommended to strengthen long-term sustainability. The Integration of Cutting-Edge Technology, Nature-Based Solutions and Circular Bioeconomy into landscape restoration presents numerous strengths. One of the primary advantages is its scalability and operational efficiency. Drone technology enables rapid and precise seed dispersal across large and inaccessible areas, significantly reducing labor costs and physical disturbance. When

TABLE 1 SWOT analysis of conceptual framework.

| Strengths                                                                                                          | Weaknesses                                                                                            |
|--------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| - Scalable and efficient restoration using drone-assisted planting                                                 | - High initial investment and limited energy infrastructure for UAV operation.                        |
| - Enhanced seedling survival and soil health through AMF symbiosis                                                 | - Requires specialized training for drone operation and microbial inoculant handling                  |
| - Closed-loop sustainability through circular bioeconomy (waste minimization, biomass reuse)                       | - Limited access to local data on native AMF strains and soil biology in remote areas                 |
| - Adaptable to diverse ecological and socio-economic contexts                                                      | - Regulatory and logistical challenges in drone deployment in some regions                            |
| - Promotes local participation and community empowerment through localized value chains                            | - Need for continuous community engagement and long-term monitoring                                   |
| - Reduces dependency on synthetic fertilizers and imported inputs                                                  | - Biophysical constraints (e.g., steep terrain, extreme weather) may hinder technology performance    |
| Opportunities                                                                                                      | Threats                                                                                               |
| - Alignment with global and national restoration targets (e.g., SDGs, UN Decade on Ecosystem Restoration)          | - Potential resistance to adoption from conventional forestry and agriculture sectors                 |
| - Potential for community cooperatives to sustain operations and share economic returns from restoration services. | - Policy gaps or lack of government support for circular bioeconomy and drone use                     |
| - Potential for public-private partnerships in drone services, seedball production, and AMF supply                 | - Overdependence on technology without adequate local capacity may reduce sustainability              |
| - Increasing global interest in nature-based and circular solutions for climate mitigation                         | - Market volatility affecting demand for biomass or other circular outputs                            |
| - Replicability across regions with similar degradation contexts                                                   | - Biodiversity concerns if AMF strains or plant species are introduced without ecological assessments |

combined with AMF, the biological effectiveness of restoration increases—AMF symbiosis improves seedling survival, enhances nutrient and water uptake, and promotes long-term soil health. Furthermore, the circular bioeconomy framework reinforces ecological sustainability by minimizing waste, reusing biomass, and promoting localized resource cycles. This system is adaptable to a wide range of ecological and socio-economic contexts, allowing for flexible implementation in diverse restoration scenarios. It also encourages community participation by integrating local actors into seedball production, drone operation, and AMF cultivation, thereby creating green jobs and strengthening local economies. Additionally, this approach reduces dependency on synthetic fertilizers and imported materials by promoting natural and locally-sourced inputs. Furthermore, community-based cooperatives and partnerships can sustain operations by channeling returns from restoration services, biomass sales, or government incentive programs.

Despite its strengths, several weaknesses must be addressed. The initial investment required for drone technology, AMF production, and specialized training is relatively high, posing a barrier to entry for many regions or communities. The success of the system also depends on the availability of skilled operators for drone deployment and microbiological management, which may be limited in remote or under-resourced areas. Access to reliable data on local AMF strains and soil conditions is often lacking, which complicates ecological matching and site-specific inoculation. Legal and logistical challenges in drone deployment, especially in regulated airspaces, can further constrain its application. Additionally, successful community-based restoration requires sustained engagement, capacity building, and monitoring—factors that may be difficult to maintain without long-term support. Finally, in areas with steep terrain or extreme weather conditions, drone operations and seedling establishment may be technically constrained.

Several external opportunities support the broader adoption of this integrated model. It aligns closely with global and national restoration agendas, including the Sustainable Development Goals (SDGs), the UN Decade on Ecosystem Restoration, and national low-carbon development strategies. The model also fits well within rural development and green job creation programs, offering income-generating opportunities tied to environmental outcomes. Public-private partnerships present a promising pathway to scale up operations, offering investment, innovation, and shared resources for drone services, AMF supply, and seedball production. Moreover, there is a growing global interest in nature-based solutions and circular economy principles, which can amplify support and funding. The system's modular design makes it replicable in other regions experiencing similar forms of land degradation.

However, there are also important external threats. One such threat is institutional inertia or resistance to change from conventional forestry or agriculture sectors, which may be reluctant to adopt emerging technologies or ecological methods. Gaps in policy or lack of government support for circular practices and drone use can slow adoption and restrict legal operations. Overdependence on external technology providers, especially without building local capacity, may undermine long-term sustainability. Additionally, market volatility—particularly in biomass or circular product markets—can affect economic viability. Finally, without adequate ecological assessments, the introduction of non-native AMF strains or plant species may pose risks to local biodiversity and ecosystem balance. In summary, while the integration of drone technology, AMF inoculation, and circular bioeconomy offers transformative potential for ecological restoration, it must be approached with careful attention to ecological fit, economic feasibility, institutional support, and social inclusion to ensure lasting impact and replicability.

## 4 Conclusion

In the face of accelerating environmental degradation, climate uncertainty, and social vulnerability, restoration must evolve into a regenerative, systemic practice that integrates ecology, technology, and local economies. The framework proposed in this article—uniting drone technology, arbuscular mycorrhizal fungi

inoculation, and circular bioeconomy principles—offers a scalable, resilient, and inclusive model for tropical upland. Each element of the triad contributes unique strengths: drones provide efficiency and spatial precision; AMF strengthens the biological foundation of restored ecosystems; and circular bioeconomy ensures that material and energy flows remain localized, renewable, and economically productive. Importantly, this integrative approach does not treat restoration as a temporary intervention, but as a long-term, community-rooted system. It embeds ecological recovery within social and economic structures, ensuring that restored landscapes provide tangible, lasting benefits for the people who depend on them. The synergistic model enhances biodiversity, rebuilds degraded soils, supports rural livelihoods, and aligns with global commitments such as the Sustainable Development Goals and the UN Decade on Ecosystem Restoration. To realize its full potential, this conceptual framework must be supported by enabling policies, investments in local capacity building, and transdisciplinary collaboration. Future research should refine UAV energy use and seedball resilience to improve field performance in tropical uplands. Restoration must be understood not only as a scientific or technical pursuit, but as a societal project—one that requires inclusive governance, adaptive learning, and a long-term commitment to ecological integrity and social justice. Enabling policies should include simplified licensing for UAV operation in restoration zones, subsidies for AMF inoculation and training, and incentives for circular bioeconomic products to support market access. Implementation can begin through pilot schemes within existing national restoration programs. Through this integrated lens, restoration becomes more than planting trees; it becomes a pathway to regenerate life, economies, and hope on degraded lands.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

JW: Funding acquisition, Writing – original draft, Conceptualization, Methodology, Resources, Writing – review & editing. Su: Conceptualization, Formal analysis, Project administration, Writing – review & editing, Supervision, Funding acquisition. W: Formal analysis, Writing – review & editing, Conceptualization, Funding acquisition, Supervision. NA: Investigation, Methodology, Writing – review & editing, Resources, Project administration. AM: Formal analysis, Resources, Project administration, Investigation, Writing – review & editing, Methodology. Sa: Methodology, Investigation, Validation, Writing – review & editing, Formal analysis, Project administration. IS: Project administration, Investigation, Resources, Writing – review & editing. FA: Writing – review & editing, Resources, Investigation, Project administration, Validation, Methodology. MS: Methodology, Investigation, Writing – review & editing, Project administration, Validation, Formal analysis. SR: Formal analysis, Funding acquisition, Resources, Writing – review & editing, Investigation, Methodology. NB: Writing – review &

editing, Funding acquisition, Investigation, Resources, Project administration, Data curation. AA: Validation, Methodology, Writing – review & editing, Supervision, Conceptualization, Writing – original draft.

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## Conflict of interest

SR and NB were employed by Indonesia Asahan Aluminium (INALUM) Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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